

# **Bibliography of NASA-Related Publications on Wind Turbine Technology 1973-1995**

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April 1995

Prepared for  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135  
Under Contract NAS3-25776

for  
U.S. DEPARTMENT OF ENERGY  
Conservation and Renewable Energy  
Office of Vehicle and Engine R&D  
Washington, D.C. 20545  
Under Interagency Agreement DE-AI01-76ET20320

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## **Acknowledgments**

This bibliography was sponsored by the Wind/Ocean/Hydro Technologies Division of the U.S. Department of Energy and by the NASA Lewis Research Center, with Mr. Daniel F. Ancona, III, as DOE Program Manager and Mr. Larry H. Gordon as NASA Project Manager. The work was performed under a subcontract to the Analex Corporation, which was administered by Mr. Russell E. Steinbach. The author expresses his appreciation to Ms. Freya A. Turner, reference librarian with the Cortez III Service Corporation, who performed the search of the NASA RECON database that produced the references which are the core of this bibliography.



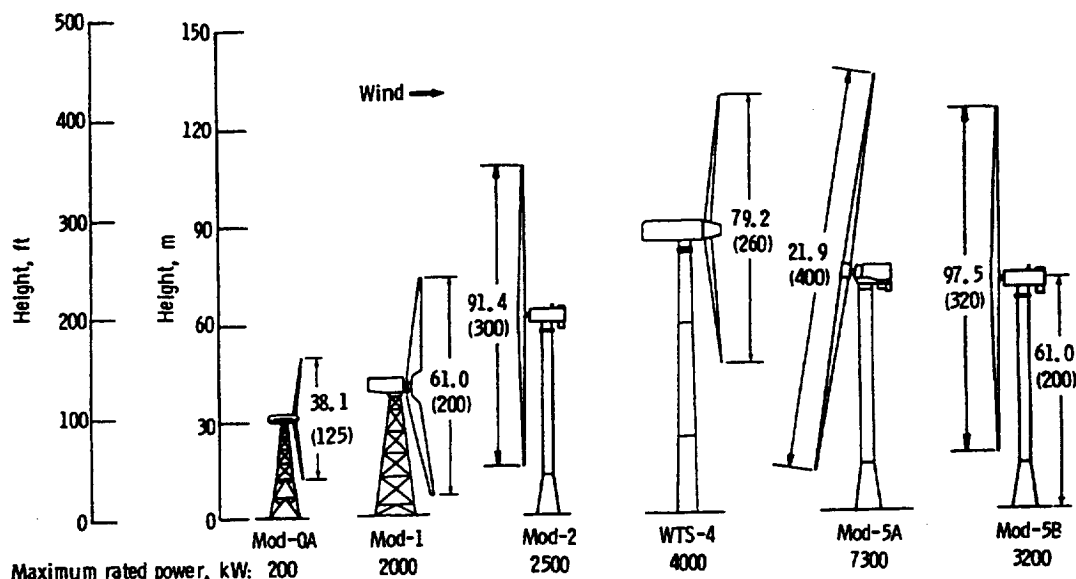
## Introduction

A major program of research and development projects on wind turbines for generating electricity was conducted at the NASA Lewis Research Center from 1973 to 1988. Most of these projects were sponsored by the U.S. Department of Energy (DOE), as a major element of its Federal Wind Energy Program. One other large-scale wind turbine project was sponsored by the Bureau of Reclamation of the Department of Interior (DOI). The peak years for wind energy work at Lewis were 1979-80, when almost 100 engineers, technicians, and administrative personnel were involved. From 1988 to their conclusion in 1995, NASA wind energy activities have been directed toward the transfer of technology to commercial and academic organizations.

Wind energy activities at NASA can be divided into two broad categories which were closely related and often overlapping: (1) Designing, building, and testing a series of 12 large-scale, experimental, horizontal-axis wind turbines (HAWTs); and (2) conducting supporting research and technology (SR&T) projects. The sketches in Figure 1 show the names, configurations, power ratings, and relative sizes of HAWTs developed within projects managed at Lewis. The progression in time is from left to right.

The purpose of this bibliography is to assist those active in the field of wind energy in locating the technical information they need on wind power planning, wind loads, turbine design and analysis, fabrication and installation, laboratory and field testing, and operations and maintenance. This bibliography contains approximately 620 citations of publications by over 520 authors and co-authors. Sources are

- NASA reports authored by government, grantee, and contractor personnel;
- Papers presented by attendees at NASA-sponsored workshops and conferences;
- Papers presented by NASA personnel at outside workshops and conferences;
- Outside publications related to research performed at NASA/DOE wind turbine sites.



**Figure 1.** Configurations and sizes of the large horizontal-axis wind turbines developed under the NASA/DOE and NASA/DOI programs. Dimensions are in meters (feet).

While the experimental HAWTs illustrated in Figure 1 were the most visible part of the NASA wind program, the majority of the publications produced were the result of SR&T activities in the disciplines of aeronautics, rotor and structural dynamics, electrical systems, controls, utility integration, economics, and environmental effects. As a result, much of the technology discussed in these publications is applicable to wind turbines of all sizes.

Brief descriptions of the scope of the principal wind turbine projects at NASA-Lewis are presented in the following sections to assist readers in using this bibliography. Two excellent summaries of the NASA/DOE wind program are given in *Large, Horizontal-Axis Wind Turbines*, by B. S. Linscott *et al.* [NASA TM-83546 1984]<sup>1</sup> and "Evolution of Modern Wind Turbines" by L. V. Divone, a chapter in *Wind Turbine Technology* [D. A. Spera, Editor; ASME Press, 1994].

The former summary emphasizes the technical aspects of the program, while the latter describes the various NASA projects as key elements of the overall Federal Wind Energy Program administered by the DOE. Excerpts from "Evolution of Modern Wind Turbines" are used in the next section to give readers an overview of the NASA/DOE wind program, and as an aid in locating publications on specific subjects.

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<sup>1</sup> References in brackets are found in the Bibliography section.

## The NASA/DOE Wind Turbine Development Program <sup>1</sup>

During the twenty-five years from 1945 to 1970, new growth in wind turbine technology took place principally in western Europe and at a very modest pace. Energy from fossil-fuel and nuclear power plants was inexpensive, and little emphasis was placed on research on alternative sources of energy. At the end of the 1960's there was, unfortunately, little useful documentation and almost no experimental data from these several decades of activities around the world. For all the large advances in the field of wind energy since the end of the nineteenth century, prospective wind turbine designers in the '70s had little firm information upon which to build, and there was little or no activity world-wide for producing electricity by wind power.

In the U.S. in 1972, engineers from the NASA Lewis Research Center were involved in measuring winds in Puerto Rico (for purposes other than wind energy conversion) and encountered some local interest in wind power. Aerodynamicists at NASA's Langley Research Center also began theoretical and experimental research on the Darrieus vertical-axis rotor. Concurrently, the National Science Foundation (NSF), under their new "Research Applied to National Needs" (RANN) program, had been examining the overall long-term issues of energy supply, and had concluded that renewable energy sources could have a major role in the future. However, individual views of that future varied enormously.

In 1973, the NSF was given the responsibility for defining and establishing a federal research program on renewable energy. That program included solar energy, of which wind energy was considered to be a constituent part. The NSF, without any laboratories of its own, turned to the Lewis Research Center for technical and management assistance [Thomas 1982]. This was the start of the DOE/NASA wind turbine development program that continued at Lewis for over 15 years.

The first step undertaken was the sponsorship of a Wind Energy Workshop by NSF and NASA-Lewis in 1973 [Savino 1973], to which were invited all those who had any prior or current interest in wind power. Pioneers from the 1930s -- such as Marcellus Jacobs, Palmer Putnam, and Beauchamp Smith from this country; and Ulrich Hütter and Arthur Stodhart from Europe -- and a younger generation of wind power developers presented papers and recommended research needs. Similar conferences and workshops, held in different countries, became annual events. By the 1980s, workshop sponsors included the American Wind Energy Association, the European Wind Energy Association, the American Society of Mechanical Engineers, and other trade associations from individual countries. The *Wind Workshop Proceedings* from these annual conferences, supplemented by those from more specialized meetings, form a detailed record of the technical development of wind power from the mid-1970s until today.

In 1974, following recommendations from that first workshop, NSF and NASA drew up an initial wind energy research plan, although with little optimism that significant funding would be forthcoming. The shock of the Arab oil embargo a few months later, however, ensured rapid growth in research funds not only in the U. S. but worldwide. In 1975 the NSF program was absorbed into the newly-formed Energy Research and Development Administration (ERDA). The core of ERDA was the Atomic Energy Commission, which had numerous government-owned/contractor-operated national laboratories and plants under its aegis. In 1977, ERDA was combined with several other Federal organizations to form the U.S. Department of Energy (DOE).

In view of the rapidly growing and broadening program, four government laboratories were selected to operate various elements of DOE's Federal Wind Energy Program. The

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<sup>1</sup> Excerpts from "Evolution of Modern Wind Turbines," by L. V. Divone, in *Wind Turbine Technology*, D. A. Spera, ed., ASME Press (New York), 1994. (Reprinted by permission of ASME Press)

Lewis Research Center was given the responsibility for developing large-scale horizontal-axis wind turbines (HAWTs) that could be integrated into utility networks as power plants. A Wind Energy Project Office was established at Lewis to carry out this mission. The initial DOE/NASA plan envisioned research and technology projects closely coupled with the design and testing of experimental wind turbines. These machines would incorporate increasingly advanced developments as they became available and would eventually reach megawatt size. Through the years, the HAWT program element managed by Lewis constituted approximately one-half of DOE's total wind program.

The development plan for large HAWTs also assumed that three cycles or "generations" of experimental turbines would be required. First-generation turbines would be necessary merely to develop an understanding of design issues and to obtain basic data. The second generation was needed to put new developments into practice. Finally, a third generation of wind turbines would be required to reach a level of performance and reliability that could be cost effective on a broad scale. The objective of this series of wind turbines was to prove the technology and to reduce technical risk to the point where significant private capital could be attracted for continued development and commercial production.

### **NASA/DOE Mod-0 100-kW Test Bed HAWT: 1975 to 1987**

One of the first activities under the Federal Wind Energy Program was the design and construction of an experimental, medium-scale HAWT to serve as a test bed. This size was clearly needed in order to reach reasonable risk levels before proceeding to large-scale turbines. Conversely, many of the test results from a medium-scale turbine could well be applied to small-scale systems. This new research wind turbine was designated the *Mod-0* to emphasize its role as a test bed. It was designed and built for NSF by an engineering and fabrication team at the NASA Lewis Research Center [Puthoff and Sirocky 1974]. Installed in 1975 at NASA's Plum Brook Test Station near Sandusky, Ohio, it became a mainstay of experimental work on HAWTs in the U.S. for the next dozen years.

#### *Original Mod-0 Configuration*

The diameter of the Mod-0 rotor was selected to be 38.1 m, and a very low rated power of 100 kW (at a rated wind speed of 8.0 m/s at hub elevation) was chosen. This low rating was determined to be suitable for such a large rotor because of the modest wind speeds in the Sandusky area. Available running time for experimental work was a much higher priority than cost optimization at that time.

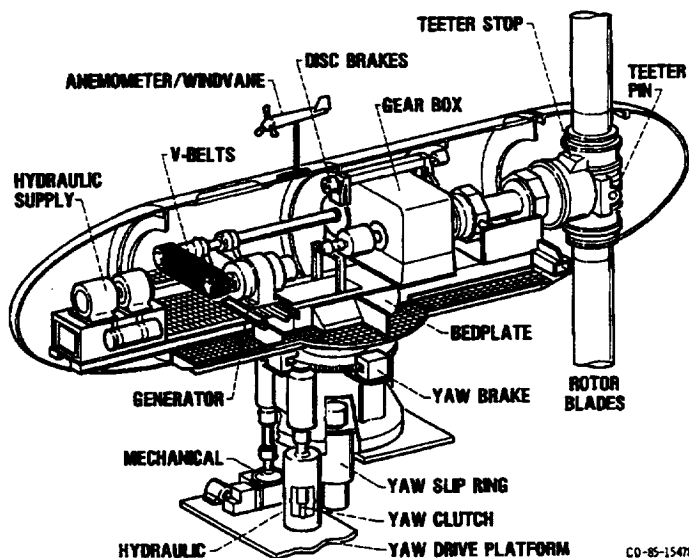
As shown in Figure 2, a two-bladed rotor located downwind of the tower was selected, following the examples of the Smith-Putnam and Hütter turbines and in accordance with economic studies that indicated a third blade was not cost-effective in large-scale systems. The Mod-0 rotor and power train were located in a streamlined nacelle atop a stiff, four-legged truss tower, with the rotor axis at an elevation of 30.5 m. Its original set of blades were of aluminum rib/spar/skin construction, following airplane wing design. While quite expensive, they were very light in weight (9,000 N each), which was considered a necessity because of the many unknowns in the structural dynamic behavior of the system.

Details of the Mod-0 power train and yaw drive subsystems are illustrated in Figure 3. The rotor drove the turbine shaft at 40 rpm which, through a parallel-shaft step-



**Figure 2.** Final assembly of the 100-kW Mod-0 HAWT test bed in 1975. It was located at the NASA-Lewis Plum Brook Test Station near Sandusky, Ohio.

up gearbox was increased to the 1,800-rpm speed of the 100-kW synchronous generator. At winds above rated, power was held constant at 100 kW by full-blade pitch under computer control, with the blades positioned by hydraulic actuators mounted on the rigid hub. Wind direction was sensed by a wind vane on top of the nacelle and monitored by the automatic yaw control system. When a change in the nacelle azimuth was needed, a pair of electric motors operated through a worm-gear reduction drive and a pinion gear to drive a bull gear attached to the bedplate. Yawing speed was 1/6 rpm.



**Figure 3.** Power train and yaw drive equipment in the Mod-0 nacelle. The pulleys and belts at the generator permitted changes in rotor speed, to study tip-speed effects and avoid structural resonances.

### *Mod-0 Research Tests and Configuration Changes*

Over the next decade, more testing to investigate new ideas and new configurations (Fig. 4) was accomplished with the Mod-0 HAWT than with probably any other wind turbine before or since. Initially designed as a downwind, two-bladed configuration with full-blade pitch, it was later tested with one (counterbalanced) blade and with two blades in both upwind and downwind configurations. New materials were developed for wind turbine blades and first tested on the Mod-0. These included laminated wood-epoxy (Spera *et al.* 1990), a material now used on many small and intermediate wind turbines, and fiberglass composite blades fabricated with transverse-filament-tape [Weingart 1981].

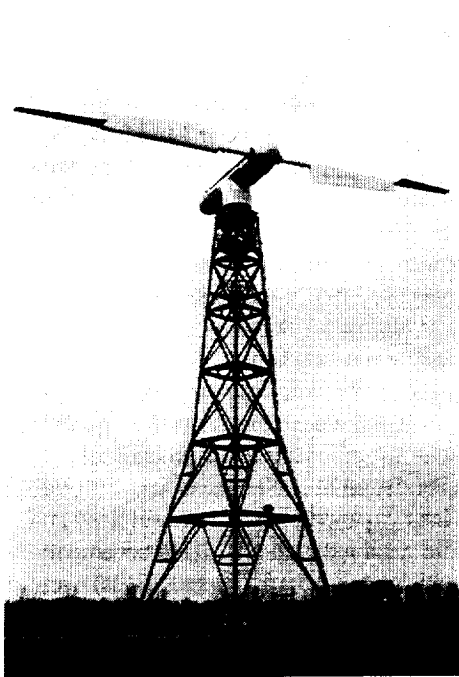
One detrimental result from the original truss tower with its central stairway was high impulsive pressure loading on the blades, from the excessive wind speed reduction in the wake behind this high-drag tower. The staircase was soon removed, which reduced cyclic loads to a tolerable level. However, tower wake-induced fatigue loads had been identified as a major design driver for downwind rotors. First-generation machines used rigid hubs in an attempt to overcome the effects of dynamic loads by a simple brute force technique. This approach was never wholly satisfactory, so the Mod-0 test configuration expanded to include a teetered hub (Fig. 5).

As structural dynamic knowledge increased, the Mod-0 truss tower was placed on a new base composed of flexural steel beams (Fig. 4(a)). This allowed the natural vibration frequency of the turbine to be lowered and "tuned" in order to simulate "soft" tower structural concepts. Such concepts would have the potential for lower tower weight and cost, but structural dynamic loads could be lower or much higher, depending on resonances and instabilities that were not well-understood with the available analysis tools. Later, the Mod-0's truss tower was replaced by a slender shell tower (Fig. 4(b)) to prove out those tools and the effectiveness of soft structural systems.

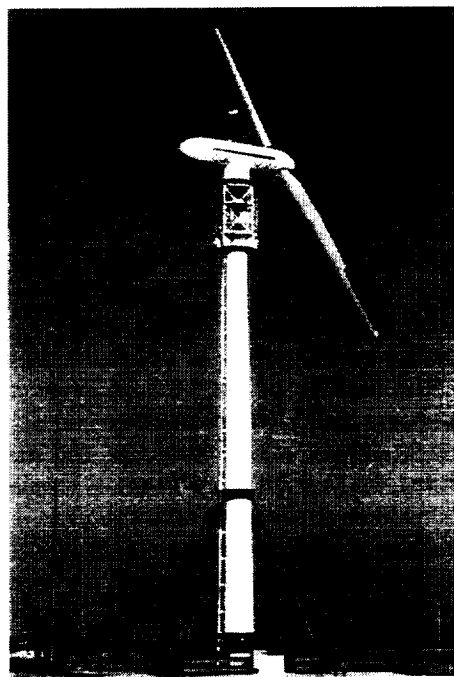
Another area which received considerable emphasis was variable-speed constant-frequency (VSCF) operation. Prior to the need for interconnection with the utility grid, many small machines operated at variable rotor speed depending on electric load and wind speed, but this had rarely been attempted on any turbine much over 15 m in diameter. The desire to operate at variable rpm is engendered by the potential for higher energy capture (always operating near peak rotor efficiency) and the potential for gust load alleviation.

Solutions to the electrical problems associated with a variable generator speed could now be envisioned that were not available in a practical way two decades earlier. The structural dynamics issues associated with the need to preclude harmonic vibrations over a range of rotor speeds were not viewed sanguinely. It was enough of a problem in the 1970s to accomplish this at one speed. In spite of this, the Mod-0 was operated as a variable-speed machine, testing several generator and power-conditioning components. More importantly, the Mod-0 tests probed the structural dynamics "envelope" on a relatively large, flexible system and thereby provided the data to develop and validate complex computer models needed to predict natural frequencies and loads under such conditions.

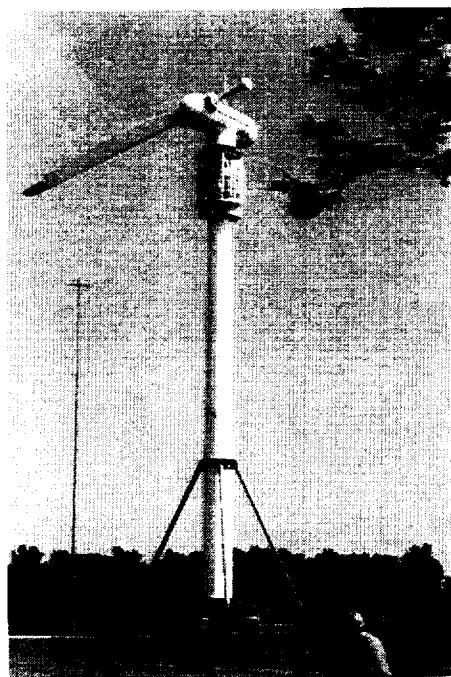
Also tested were rotors with partial-span pitch control, flaps (often less-correctly termed ailerons), fixed-pitch stall regulation, and free-yaw response to changing wind directions. Tests at Plum Brook determined the effects of precipitation, various airfoils, blade root and tip design innovations, and auxiliary aerodynamic devices such as vortex generators. The validation of computer models and control algorithms, though less visible than hardware changes, was probably one of the most valuable contributions of the test bed program. After a useful life of over a dozen years, the Mod-0 experimental HAWT was dismantled in February 1987, leaving as its legacy an extensive set of documentation that forms a principal basis of modern wind turbine technology.



(a)



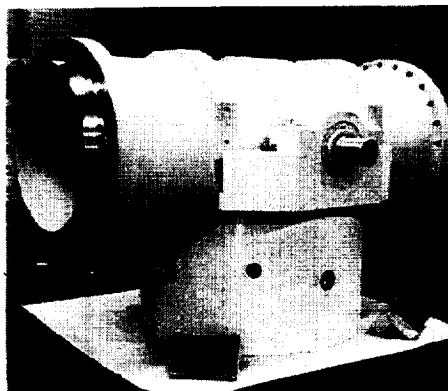
(b)



(c)

**Figure 4. Different Mod-0 configurations during a decade of research.**

(a) 1979: Upwind rotor, steel spar blades, partial-span pitch, teetered hub, and a spring base; simulated the "soft" second-generation Mod-2 HAWT. (b) 1982: Shell tower, flap control, inboard blade sections of laminated wood. (c) 1985: One-bladed, teetered rotor with tip control.



**Figure 5. Mod-0 teetered hub.**

## NASA/DOE Mod-0A First-Generation HAWT Project

During the 1970's, progress continued on several developmental cycles of medium- and large-scale machines. Soon after the initial testing of the 38.1-m diameter Mod-0 HAWT test bed, the U.S. Department of Energy decided to install a pair of upgraded replicas (later increased to four through Congressional actions) into actual utility operation. These machines were designated the Mod-0A wind turbines (Fig. 6), and each had a rated power of 200 kW, twice that of the Mod-0. While their power was still quite small as viewed by a utility, these would be the largest wind turbines integrated into a utility since the Smith-Putnam turbine of 1939. In fact, at the time there was almost no experience in the U.S. in operating a wind turbine of any size in an electric utility environment.

The purpose of the Mod-0A program was to identify and resolve technical and operational utility interconnection issues. These included questions of power quality, transient effects, safety, re-closure, and startup/synchronization/shutdown procedures. In addition, the Mod-0A HAWTs would form a visible validation of such operations. Through a competition aimed at the utility industry, 17 sites (later expanded to 35) were selected and instrumented with anemometer towers for detailed site wind assessments. This became the base from which the locations of the Mod-0As (and later NASA/DOE machines) were selected in follow-on competitions. The four Mod-0A HAWTs were installed from 1977 to 1979 at Clayton, New Mexico; Block Island, Rhode Island; Culebra Island, Puerto Rico; and near Kahuku on the northern tip of the island of Oahu, Hawaii [Shaltens and Birchenough 1983]. Mod-0A sites were selected at relatively small utilities or isolated locations, so that some understanding of the problems of significant penetration of wind power into a grid could be investigated. Some issues could have remained unidentified if the wind turbine rating was an extremely small percentage of the local generating capacity.



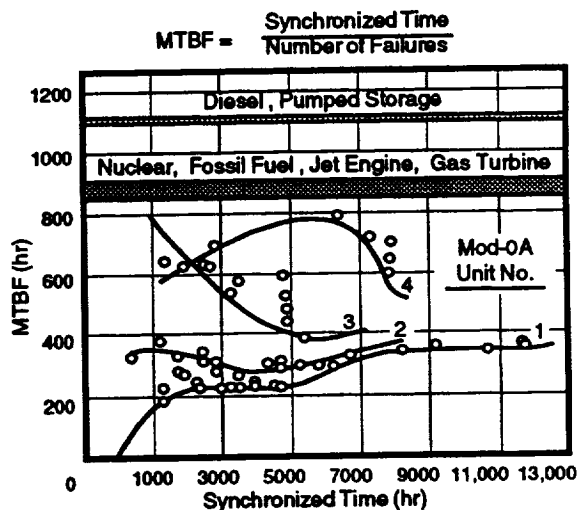
**Figure 6.** The 200-kW 38.1-m diameter Mod-0A wind turbine on Block Island, Rhode Island. It was one of four turbines of the same design installed on small grids in the U.S. to identify and resolve utility interconnection and operation issues.

The first Mod-0A unit was designed and fabricated at NASA Lewis, and a contract was then awarded to Westinghouse Electric Corporation to construct the remainder. While ostensibly identical, each machine received detailed improvements based on the experiences of the prior installation. The Lockheed Corporation, which had built the original fabricated-aluminum blades for the Mod-0, provided the initial sets of Mod-0A blades to the same general design but with thicker skin panels. However, the downwind configuration and rigid hub introduced high and (at that time) uncertain dynamic loads that caused fatigue cracks in the aluminum skins and ribs near the blade roots. Eventually all four rotors were fitted with laminated wood-epoxy or fiberglass blades and operated successfully for extended periods.

Probably the most severe operational test of the Mod-0A came in the installation at Block Island, which was one of the reasons for the selection of that site. The Block Island grid is powered by several diesel-electric generators and is not interconnected with any other utility. Block Island has many summer vacationers and only a very small year-round population. Thus, summer peak loads reach over 1,800 kW, while during night hours in winter (which is also the high-wind season) the total load can go down to only a few hundred kilowatts. Occasionally the Mod-0A at 200 kW was producing over 50 percent of the power for the island. This large penetration introduced several problems in terms of both voltage and frequency stability and diesel operating problems caused by excessive throttling. The Block Island Mod-0A was therefore derated to 150 kW during winter operations, unless under special test.

When the Mod-0A project was completed in June 1982, the four machines had accumulated over 38,000 hours of operating time and had fed some 3.6 million kWh into their host utility grids [Shaltens and Birchenough 1983]. At a Hawaiian Electric Company site near Kahuku, the fourth and most reliable Mod-0A (Fig. 7) achieved a capacity factor of 0.48 during its last months of operation and was a principal cause of the developing interest in wind power in the Hawaiian Islands. The highly successful operation of the Kahuku turbine also led its builder, the Westinghouse Corporation, to privately develop a 600-kW HAWT and Hawaiian Electric Industries (the parent corporation of the utility) to participate in the later Mod-5B

program and encourage private wind power developers. The most important contribution of the four Mod-0A HAWTs was that they produced the first visible evidence that wind turbines, while not yet cost-effective, could be successfully integrated into a utility's normal operations and could produce high-quality AC power of value to that utility. They also provided a technology base that paved the way for the growth in size of privately-developed wind turbines, from the 10- to 15-m diameter and 10- to 25-kW sizes of the early 1970s to the 100- to 300-kW and 20- to 30-m diameter turbines that were developed and installed in the late 1980s.

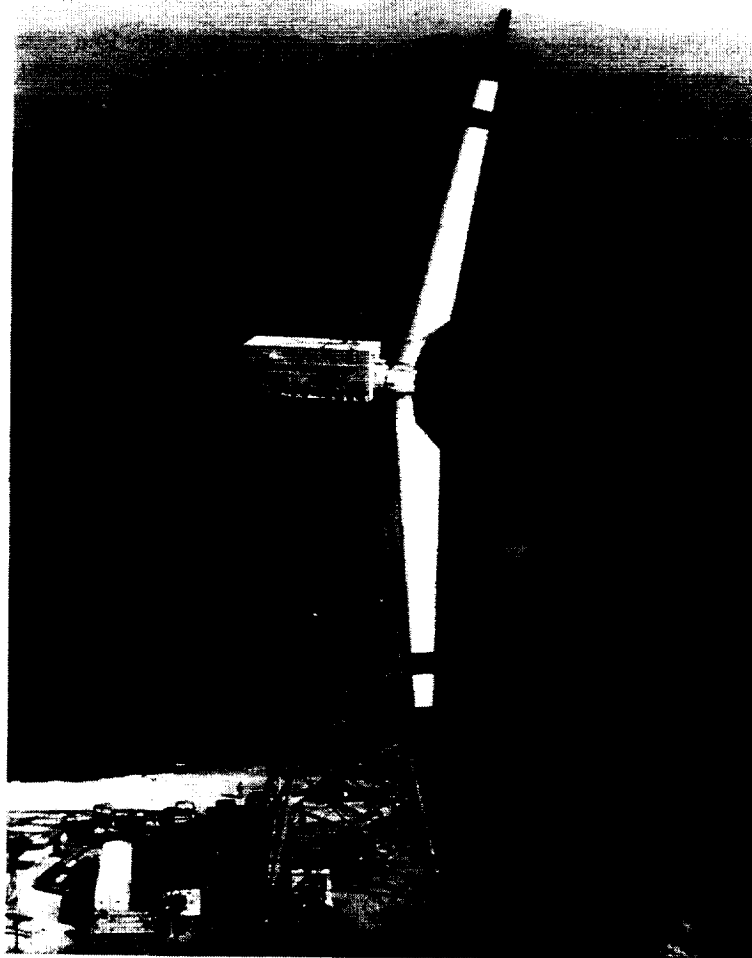


**Figure 7. Mod-0A mean times between failure.** Unit No. 4, on Oahu in the Hawaiian Islands, was the most durable.

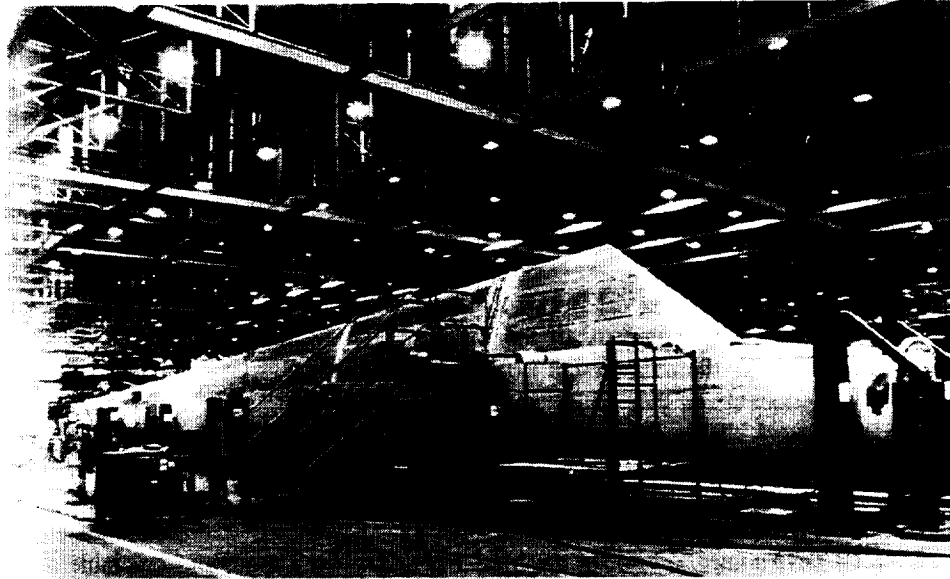
## NASA/DOE Mod-1 First-Generation HAWT Project

### *The Wind Turbine System*

Development of the Mod-1 Experimental HAWT (Fig. 8), the first megawatt-scale wind turbine on a utility grid since the 1939 Smith-Putnam turbine, began in parallel with the installation of the Mod-0As. Rated at 2.0 MW and with a rotor 61 m in diameter, the Mod-1 HAWT used the same general design configuration as the Mod-0: a two-bladed, rigid hub rotor with full-blade pitch control, mounted downwind of a stiff, truss tower. The experimental system was designed and built by the General Electric Company, with welded-steel blades fabricated by the Boeing Aerospace Company (Fig. 9). It was installed on a small mountain called Howard's Knob near Boone, North Carolina, and was dedicated on July 11, 1979. The local utility, the Blue Ridge Electric Membership Cooperative, operated the Mod-1 for two years, proving that megawatt-scale wind turbines could be successfully interfaced with a large, conventional utility power system [Collins *et al.* 1982].



**Figure 8.** The 2.0-MW 61-m diameter Mod-1 experimental HAWT in 1979 on Howard's Knob overlooking Boone, North Carolina. It was the first megawatt-scale wind turbine since the Smith-Putnam HAWT in the 1940s.



**Figure 9.** A 30-m long Mod-1 blade during final assembly at the Boeing Aerospace plant in Seattle, Washington. The structural spar was fabricated from welded steel plates, to which trailing edge sections of foam-filled fiberglass were bonded. [Linscott *et al.* 1984]

The Mod-1 design, however, was not completely successful. While it achieved its rated power and operated safely in an unattended, automatic mode, the wind velocity decrements behind the stubby truss tower applied high, impulsive loads to the rigidly-mounted blades. While no major blade problems actually occurred, it was clear that this design configuration would not have the 20- to 30-year life necessary in a commercial turbine. Improperly-torqued bolts attaching the turbine shaft to the hub did fail near the completion of the test program, but no major damage ensued because the rotor was supported by a large bearing mounted directly to the nacelle structure. However, it was deemed wisest to dismantle the turbine. The 60-m welded steel rotor, at that time the largest that had ever been built, was placed on display at the Science Museum in Raleigh.

#### *Environmental Problems*

The Mod-1 encountered two environmental problems: interference with television signals and acoustic noise. In parallel with the technology portion of the wind energy development program at the NSF, a major study was initiated with Battelle Memorial Institute in Columbus, Ohio, to identify any conceivable environmental effects that could be caused by either an individual wind turbine or by the large-scale use of wind power [Rogers *et al.* 1977]. These ranged from the possibility of affecting the micro-climate to striking birds. The latter was, in fact, a major initial worry regarding the large scale use of wind power, regardless of the size of the individual turbines. Extensive tests on and around the Mod-0 HAWT showed that there were no significant ecological effects. However, while the Sandusky, Ohio, locale is rich in herbivorous and migratory birds, it has few local raptors. Some later wind power stations in California did encounter bird strikes with raptors, for which potential ameliorating approaches are under study.

Three potential problem areas were identified: the possibilities of acoustic noise, electromagnetic interference with local microwave radio or TV reception, and uncertain public acceptance of the aesthetics of wind turbines on the landscape. Following the initial

Battelle study, specialized research projects concentrating on these potential issues were undertaken [Balombin 1980, Senior *et al.* 1977, Ferber 1977].

The first environmental issue to be actually encountered at the Mod-1 site was the electromagnetic interference (EMI) problem. Results of the research showed that, while there would not be a significant effect across most frequencies (unless the turbine was close to, and literally in the path of, a microwave or other antenna), the upper VHF and lower UHF television bands were the most vulnerable and could be affected. Analytical tools began to be developed to predict the possibility of EMI in any given installation. Early analysis showed that, of the 17 sites under consideration by DOE, the Block Island site would likely experience TV interference, given the already marginal television reception in that area. Because it was ideal in all other respects, Block Island was selected for the third Mod-0A site partially to allow measurement of actual TV interference under complex real-world situations. A television cable system was first installed in cooperation with the nearby town in order to mitigate any effects on the public.

Like Block Island, the area around Boone had TV signals of marginal strength, and some EMI was encountered there also. EMI measurements around the large-scale Mod-1 turbine with its steel blades, coupled with the Block Island measurements and laboratory tests at the University of Michigan, led to the development of accurate tools for the evaluation of future sites. The EMI potential was found to be a predictable function of blade size and material, rotor speed, and the local transmitter/receiver/turbine geometry.

A second environmental issue at the Mod-1 site was, for a time, an intractable noise problem. Prior wind turbines were generally relatively quiet, and the Mod-1 itself was not noticeably noisy close-up. Under certain conditions, however, it emitted low frequency pressure pulsations. At seemingly random intervals, this would produce unacceptable noise at various locations a considerable distance from the site, even though at other locations or times, no noise was detectable. The source was determined to be coupling between the blade passage and wakes from the heavy tubular legs of the truss tower. Atmospheric conditions, particularly inversions, combined with the complex mountain terrain could then focus the noise at some locations distant from the site. Research conducted in the area eventually led to the development of refined and verified methods for analyzing and predicting wind turbine noise. The Mod-1 noise problem was eventually solved by reducing the rotor speed, an operation that required replacing the generator.

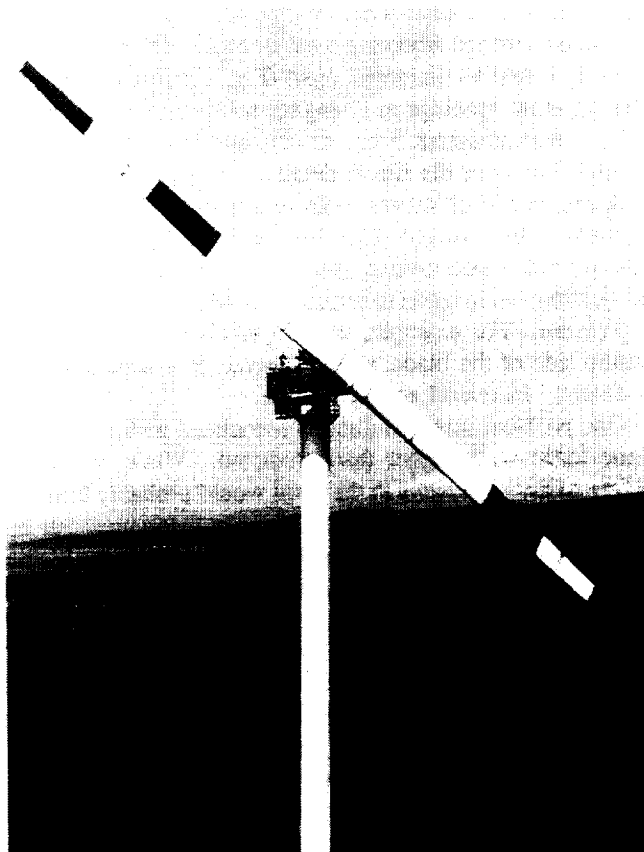
## NASA/DOE Mod-2 Second-Generation HAWT Project

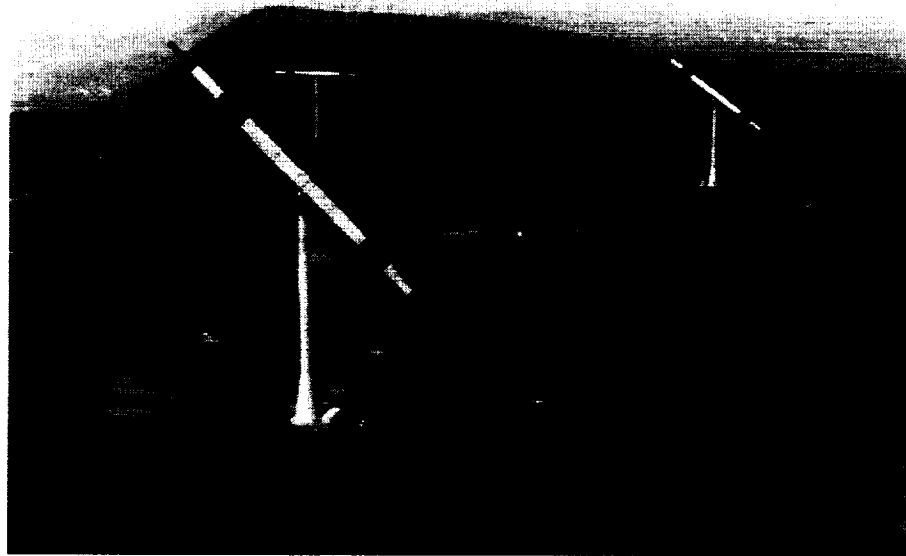
Even before the first-generation Mod-1 HAWT began its test program, development was started at NASA Lewis on a second-generation large-scale machine, to be named the Mod-2 HAWT, which would represent a major advance from earlier systems. Boeing Aerospace Corporation received the development contract, and a site was selected at Goodnoe Hills, near the Columbia River Gorge and the town of Goldendale, Washington. The Bonneville Power Administration was the cooperating utility, with the power to be fed into the grid of the Klickitat County Public Utility District.

The state of knowledge of structural dynamics of wind turbines had then reached the stage where a "soft" structural design could be attempted on a large turbine. An upwind rotor configuration was selected to reduce the possibility of noise and cyclic loads from tower shadow. As shown in Figure 10, the two-bladed rotor concept of the Mod-0 and Mod-1 was retained. Instead of full-span pitch control, however, partial-span tip control was selected, which allowed a teetered hub that was less expensive and structurally superior.

Economic optimization from the utility viewpoint, coupled with the federal role of pursuing technology levels that were beyond the risk limits acceptable to a private company, led to the selection of a power rating of 2.5 MW at a rated wind speed of 12.3 m/s (at the hub) and a rotor diameter of 91.4 m. The 900-kN (100-ton) rotor was fabricated from welded steel plates in five separate sections: a hub, two mid-blades, and two pitchable tips. These were bolted together at the site and lifted into place in one piece [Boeing 1982].

**Figure 10. The 2.5-MW Mod-2 HAWT, the second-generation turbine in the large-scale segment of the Federal Wind Energy Program. Its welded-steel, teetered rotor was 91.4 m from tip to tip, with pitchable tips.**





**Figure 11.** Arrangement of the three Mod-2 HAWTs on the Goodnoe Hills site near Goldendale, Washington. The triangular pattern permitted research on wake interference effects at different downwind distances. (*Courtesy of Boeing Aerospace Corporation*)

Three Mod-2 turbines were built and tested at the Goodnoe Hills site in order to study the integration of a large-scale wind power station into a utility network and investigate any interactions between adjoining wind turbines. The three turbines were placed in a triangular pattern 5, 7, and 10 diameters apart (Fig. 11) so that wake interactions could be examined under different spacings as changing wind directions placed the various units behind one another. Anemometers, kites, smoke, and balloons were used extensively to characterize the wind flow over the site in detail.

A number of problems were encountered, particularly during the first two years of operation. These included fatigue cracks in the turbine shafts originating at component mounting holes, and leaking grease seals causing failures in the tip pitch bearings. Other modifications were made to improve the Mod-2 system, based on experience gained during the program. For example, lines of small vortex generators were installed on the low-pressure side of the blade, which delayed flow separation, enhanced control stability, and significantly increased energy capture.

One problem that was directly associated with the design of the Mod-2 was that rotor fatigue loads were higher than predicted. While no structural failures occurred, repair welding of fatigue cracks in the rotor would probably have been required in approximately 10 years, rather than the predicted 30 years. Measurements of dynamic loads on the Mod-2 showed the foundations of the problem. The structural loading estimates of that time used relatively simple models of the wind. The effects of atmospheric turbulence as seen by a rotating blade -- what is now known as rotationally-sampled turbulence -- were not adequately represented in wind models. Based on the Mod-2 test results, major improvements in these models have been made in recent years. However, achieving long fatigue life in the presence of small-scale turbulence remains a principal technical challenge to the development of advanced wind turbines that are still reliable and cost-effective.

The Mod-2 test program went on to accomplish its major objectives. The three HAWTs together accumulated over 16,000 hours of operating time and supplied over 10 million kWh to the local grid, over 60 percent of that amount in the final year of testing. The 7.5-MW cluster proved conclusively that groups of modern wind turbines could operate together in a totally automatic, unattended mode. The Goodnoe Hills data on rotor wake effects has led to improved wake models being applied now to commercial wind power stations.

Two additional Mod-2 turbines were built by Boeing for utility companies. One, purchased by the Pacific Gas and Electric Company, was installed on a test site in Solano County, northeast of San Francisco. A second, for the Bureau of Reclamation, was installed near the WTS-4 HAWT at Medicine Bow, Wyoming, for comparative testing. All Mod-2 turbines were later dismantled.

## **NASA/DOE Mod-5 Third-Generation HAWT Project**

In the late 1970s conceptual studies were conducted on advanced large- and medium-scale turbines, designated as Mod-3 and Mod-4. Two aerospace contractors were then chosen to design and develop advanced multi-megawatt wind turbines which became known as the General Electric Mod-5A and the Boeing Mod-5B HAWTs. The General Electric Company withdrew from the Mod-5A project at the conclusion of its design stage, citing a poor near-term prospect of obtaining additional wind turbine sales, as well as the expected expiration of energy tax credits as factors in its decision. Thus, one third-generation turbine, the Mod-5B, was completed under the Federal Wind Energy Program. Hawaiian Electric Industries became Boeing's utility partner.

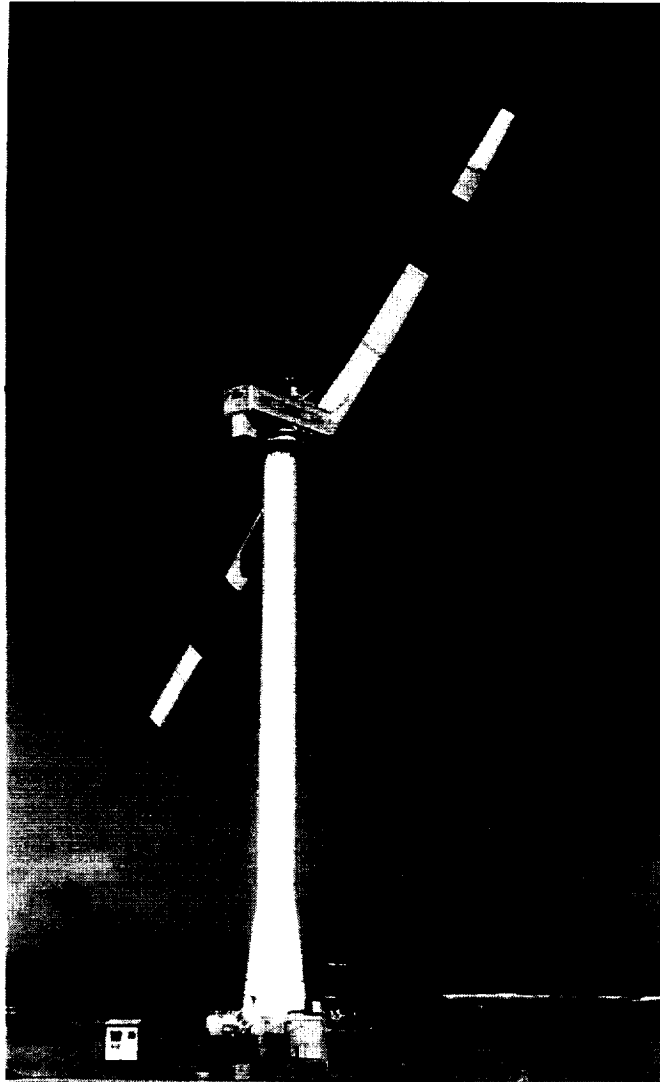
The Mod-5B (Fig. 12), installed at the Kahuku wind power station on Oahu, has an overall configuration similar to that of the Mod-2, with a two-bladed, partial-span controlled, teetered, and upwind rotor atop a steel shell tower [Boeing 1988]. The pitchable tip sections were extended 3 m longer than those on the Mod-2 rotor, leading to a rotor diameter of 97.5 m. This makes the Mod-5B HAWT currently the largest wind turbine in the world. Its rated power is 3.2 MW, up 28 percent from the Mod-2 rating.

The major advancement in technology achieved by the Mod-5B is that it is the first large-scale wind turbine to operate successfully at variable speed. The speed varies from 13 to 17.3 rpm depending on wind speed, thus improving energy capture as well as reducing structural loads. Maintaining constant 60-cycle power is accomplished through the use of a doubly-wound generator, associated cycloconverter power electronic equipment, and advanced control algorithms. Vortex generators and trailing-edge tabs improve the aerodynamic performance of the rotor. Most importantly, the Mod-5B was designed using advanced structural-dynamic computer codes like Dylosat [Finger 1985] and incorporating experience from the Mod-2 test program [Bovarnick and Engle 1985]. Thus it appears to be the first large-scale turbine with a reasonable expectation of a 30-year structural lifetime.

Final assembly commenced in January, 1987, at the site on the north shore of the island of Oahu, not far from where the fourth Mod-0A 200-kW wind turbine had been located. The turbine nacelle and rotor had been shipped by barge to Oahu from the mainland in subassemblies, together with the very large ringer crane needed for final assembly. The hub and mid-blade subassemblies of the 1.4-MN rotor, also of all-steel construction, were welded together on-site, rather than having bolted joints, as was the case with the Mod-2.

First wind-powered rotation of the Mod-5B HAWT occurred on July 1, 1987. The test program began in earnest in August, 1987, and consisted of two 500-hour phases. The first phase accomplished checkout of the turbine through its operating envelope and adjustment of controls and the variable-speed generating system. The second phase consisted of testing under a utility acceptance test scenario, the purchase price to the utility being a function of both performance and availability during a test period of at least 500 hours. The turbine achieved an energy capture performance of 106% of the basic contract requirement, producing 988 MWh during 660 hours of testing. It also achieved an availability of 95 percent, 5 percent over the basic requirement, an unparalleled level for that early a stage of testing of a new, advanced, and very large wind turbine.

In January of 1988, the Mod-5B was sold to the project's utility partner to operate as an integral part of the power generation mix on Oahu. During its first 55 months of service as a commercial power plant, the Mod-5B operated for 18,920 hours and produced 24,533 MWh of electricity [Spera and Miller 1992]. During March of 1991, the Mod-5B produced 1,256 MWh of electricity, which is the record energy production by a single wind turbine.

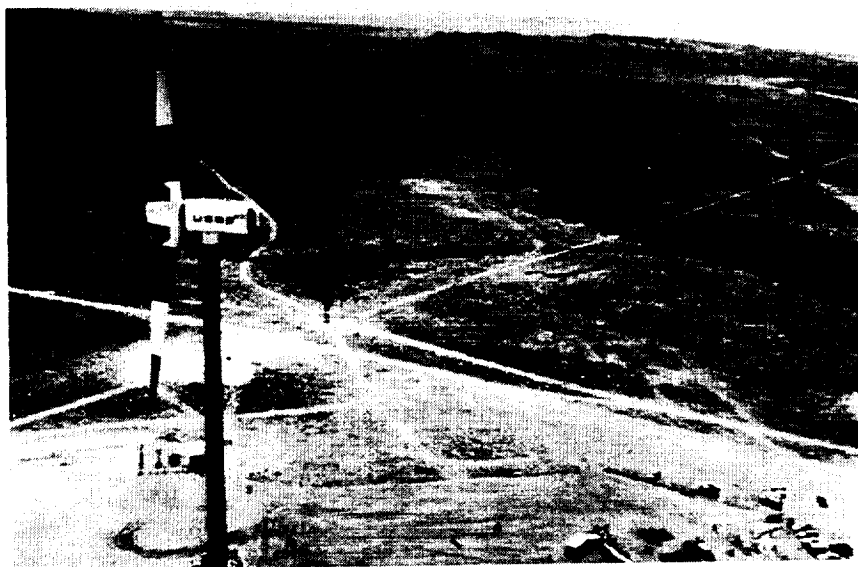


**Figure 12.** The 3.2-MW Mod-5B third-generation wind turbine contains many advanced design features, including a variable-speed constant-frequency generating system. With its swept area of  $7,470 \text{ m}^2$ , it is the largest wind turbine in the world.

## The NASA/DOI System Verification Unit Program

In the late 1970s, the Bureau of Reclamation -- an organizational element of the U.S. Department of the Interior (DOI) -- determined that wind energy has the potential to reduce the amount of water required to flow through their hydroelectric turbines. This in turn would increase the amount of water available for use in agriculture and to support fish habitats. The Bureau was authorized to conduct experimental tests of megawatt wind turbines connected to its hydroelectric network. These pilot projects for future large-scale clusters of wind turbines were designated as "system verification units (SVUs)". NASA Lewis was asked to provide project management and technical support to the Bureau of Reclamation for the procurement, construction, and initial testing of SVU wind turbines.

A site near Medicine Bow, Wyoming, was selected, and proposals were solicited from industrial firms to design, fabricate, and install two megawatt-scale HAWTs at that site. Competitive bids were evaluated by Lewis and Bureau personnel, and an industry team was selected that consisted of the Hamilton Standard Division of United Technologies Corporation and the Karlskronavarvet (KKRV) Company from Sweden. The team designed, fabricated, and installed an advanced HAWT designated as the WTS-4 (Fig. 13). With a rating of 4 MW, the WTS-4 was the most powerful wind turbine ever built. The WTS-4 rotor was 78.2 m in diameter and operated downwind of the tower. The rotor consisted of two filament-wound fiberglass blades mounted on a teetered hub, with full-blade pitch control. The 80-m steel shell tower was of the "soft-soft" design, with a fundamental natural frequency less than the rotor rotational speed. This tower design was selected to reduce wind gust loads, tower weight, and tower cost.



**Figure 13.** The 4.0-MW WTS-4 HAWT near Medicine Bow, Wyoming. This turbine and a companion 2.5-MW Mod-2 HAWT were used by the U.S. Bureau of Reclamation as system verification units for the future integration of wind and hydroelectric power.

WTS-4 operations began in September 1982 with a series of acceptance tests [Young and Hasbrouck 1983] followed by research tests and analysis [Hubbard and Shepherd 1983, Doman 1985, Murtha-Smith 1985, DeValentin *et al* 1986, and Hamilton Standard 1985 and 1987] combined with energy production. Operations for the Bureau of Reclamation were halted by damage to the power train during an overspeed incident. The machine was later sold to the Medicine Bow Energy Company. After extensive repairs, it was operated commercially until January 1994 when it was badly damaged after the control system malfunctioned during high winds.

In its lifetime the WTS-4 HAWT produced 15,800,000 kWh of power during 6,700 hours of on-line time, for an average operating power output of 2.36 MW. Its highest monthly energy production was 1,210,000 kWh during December 1993, nearly equal to the record for monthly production by a single wind turbine (1,256,000 kWh generated by the Mod-5B HAWT in March 1991).

In addition to the WTS-4, the Bureau of Reclamation requested NASA Lewis to manage the procurement, installation, and testing of a Boeing 2.5-MW Mod-2 HAWT as a second SVU at the same Medicine Bow site. Boeing completed the installation of this turbine in December 1981 [Johnson and Young 1985].

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**AERODYNAMIC ANALYSIS OF A HORIZONTAL AXIS WIND TURBINE BY USE OF HELICAL VORTEX THEORY -- VOLUME II: COMPUTER PROGRAM USERS MANUAL**

Afjeh, A. A. , Keith, T. G. Jr. , Jeng, D. R. , and White, J. A.

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**WAKE EFFECTS ON THE AERODYNAMIC PERFORMANCE OF HORIZONTAL AXIS WIND TURBINES**

Afjeh, A. A.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,

NASA CP 2106, DOE CONF-7904111. pp. 155-171.

**ALCOA WIND TURBINES**

Ai, D. K.

The Alcoa wind energy program, initiated in 1975, began with the fabrication of VAWT blades, and two years later broadened its scope to the design and fabrication of complete Darrieus systems. Configuration parameters, system operations, general design criteria, performance analysis, and cost estimates are discussed for a series of proposed turbines from 18 m to 82 m in diameter.

89N24459<sup>2</sup> NASA-TM-101957

**COMPOSITE BLADE STRUCTURAL ANALYZER (COBSTRAN) DEMONSTRATION MANUAL**

Aiello, R. A.

The input deck setup is described for a computer code, composite blade structural analyzer (COBSTRAN) which was developed for the design and analysis of composite turboprop and turboprop blades and also for composite wind turbine blades. This manual is intended for use in conjunction with the COBSTRAN user's manual. Seven demonstration problems are described with pre- and postprocessing input decks. Modeling of blades which are solid through-the-thickness and also aircraft wing airfoils with internal spars is shown. Corresponding NASTRAN and data input decks are also shown. Detail descriptions of each line of the pre- and post-processing decks is provided with reference to the Card Groups defined in the user's manual. A dictionary of all program variables and terms used in this manual may be found in Section 6 of the user's manual.

89N23621 NASA-TM-101461

**COMPOSITE BLADE STRUCTURAL ANALYZER (COBSTRAN) USER'S MANUAL**

Aiello, R. A.

The installation and use of a computer code, COBSTRAN (COmposite Blade STRuctural ANalyzer), developed for the design and analysis of composite turboprop and turboprop blades and also for composite wind turbine blades was described. This code combines composite mechanics and laminate theory with an internal data base of fiber and matrix properties. Inputs to the code are constituent fiber and matrix material properties, factors reflecting the fabrication process, composite geometry and blade geometry. COBSTRAN performs the micromechanics, macromechanics and laminate analyses of these fiber composites. COBSTRAN generates a NASTRAN model with equivalent anisotropic homogeneous material properties. Stress output from NASTRAN is used to calculate individual ply stresses, strains, interply stresses, through-the-thickness stresses and failure margins. Curved panel structures may be modeled providing the curvature of a cross-section is defined by a single value function. COBSTRAN is written in FORTRAN 77.

NASA-CR-168054, 1982.

**AERODYNAMIC ANALYSIS OF A HORIZONTAL AXIS WIND TURBINE BY USE OF HELICAL VORTEX THEORY -- VOLUME I: THEORY**

Aliakbarkhanafjeh, A. , Jeng, D. R. , and Keith, T. G. Jr.

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<sup>2</sup> NASA RECON data-base accession number.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 115-120.

**AN ELECTRICAL GENERATOR WITH A VARIABLE SPEED INPUT - CONSTANT FREQUENCY OUTPUT**  
Allison, H. J.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 45-50.

#### **THE FEDERAL WIND ENERGY PROGRAM**

Ancona, D. F. III

Recent advances are described in the areas of large and small machine development, wind characteristics, utility interconnection, and environmental concerns.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 1-23.

#### **OVERVIEW OF FEDERAL WIND ENERGY PROGRAM**

Ancona, D. F. III

This discussion provides a brief overview of what the Federal Wind Program is today,, what the objectives are and what strategies are being followed. Some of the changes in the program structure and some of the additions to the program are also included. The overall objective of the Government program is to assist industry to the point where it can produce wind machines and sell them to utilities and to private individuals, so that significant quantities of electrical energy can be captured from the wind. Topics covered are mission and application studies; legal, social, and environmental issues; wind characteristics; technology development; innovative concepts; development of wind turbine systems; and program resources.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), pp. 97-104.

#### **DOUBLY-FED VARIABLE SPEED GENERATING SYSTEM TESTING**

Andersen, T. S. , Hughes, P. S. , Klein, F. F. , and Mutone, G. A.

This paper describes a verification test program using a 500 hp motor test train, after preliminary verification with computer simulation.

Proceedings, Wind Energy Expo '83 and National Conference, 1983, American Wind Energy Association (Washington, DC), pp. 27-33.

#### **RECENT ADVANCES IN VARIABLE SPEED GENERATOR TECHNOLOGY FOR LARGE WIND TURBINES**

Andersen, T. S.

This paper describes laboratory verification of a variable-speed, constant-frequency electrical and control system for a wind turbine in two steps: First, actual control hardware and software were verified with a hybrid simulation of a full wind turbine generator system; and second, the controls were combined with power thyristor bridges configured as a cycloconverter and motor-generator test train to implement a variable speed generator and a simulated wind-turbine/drive train. Within the constraints of existing equipment, major features demonstrated include variable-frequency motoring up to 50% speed; synchronization below, at, and above synchronous speed; net power output up to 120 kW with stable response to 50 kW step changes and similar responsive control of VARS; steady power and VAR outputs throughout wind speed transients; less than 5% total harmonic distortion; and damping of simulated drive train oscillations.

Proceedings, Wind Energy Expo '82 and National Conference, 1982, American Wind Energy Association (Washington, DC), pp. 33-47.

#### **VARIABLE SPEED ELECTRICAL GENERATOR SYSTEMS FOR LARGE WIND TURBINES**

Andersen, T. S. , Hughes, P. S. , Kirschbaum, H. S. , and Mutone, G. A.

An electrical system is described in detail which employs a doubly-fed (wound rotor) generator with a solid-state cycloconverter in the rotor circuit and a stator tied to the interfacing utility network. Computer simulations are used to show the advantages of this variable-speed system for wind turbines, which are expected to be improved aerodynamic efficiency, a dramatic reduction in drive train torque resonances and transients, and isolation of the electrical output from dynamic wind loads on the turbine.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 125-138.

**MULTIPLE AND VARIABLE SPEED ELECTRICAL GENERATOR SYSTEMS FOR LARGE WIND TURBINES**

Andersen, T. S. , Hughes, P. S. , Kirschbaum, H. S. , and Mutone, G. A.

A cost-effective method is presented employing variable speed operation to achieve wind turbine operational benefits. Specific large-size conceptual design extend earlier studies of multiple and variable speed generators. costs and performance benefits from both two-speed and variable speed configurations are defined through system designs and simulations.

NASA-CR-165127 DOE/NASA/0163-1, 1980.

**EXECUTIVE SUMMARY OF MOD-0A 200-kW WIND TURBINE GENERATOR -- DESIGN AND ANALYSIS REPORT**

Andersen, T. S. , Bodenshatz, C. A. , Eggers, A. G. , Lampe, R. F. , Schornhorst, J. R. , Hughes, P. S. , and Lipner, M. S.

NASA-CR-165127 DOE/NASA/0163-2, 1980.

**MOD-0A 200-kW WIND TURBINE GENERATOR -- DESIGN AND ANALYSIS REPORT**

Andersen, T. S. , Bodenshatz, C. A. , Eggers, A. G. , Lampe, R. F. , Schornhorst, J. R. , Hughes, P. S. , and Lipner, M. S.

NASA-CR-165127 DOE/NASA/0163-3, 1980.

**MOD-0A 200-kW WIND TURBINE GENERATOR -- DRAWING REPORT**

Andersen, T. S. , Bodenshatz, C. A. , Eggers, A. G. , Lampe, R. F. , and Hughes, P. S.

NASA=TM-81425, 1980.

**EVALUATION OF A HIGH PERFORMANCE FIXED-RATIO TRACTION DRIVE**

Anderson, N. E. , Loewenthal, S. H. , and Rohn, D. A.

NASA-CR-134957 ERDA/NASA/9235-75/2, 1975.

**100-kW METAL WIND TURBINE BLADE DYNAMICS, WEIGHT/BALANCE, AND STRUCTURAL TEST RESULTS**

Anderson, W. D.

NASA-TM-83460, 1983.

**MOD-2 WIND TURBINE DEVELOPMENT**

Andrews, J. S. , Gordon, L. H. , and Zimmerman, D. K.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 611-635; and Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. II, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 611-632.

**DEVELOPMENT TESTS FOR THE 2.5 MEGAWATT MOD-2 WIND TURBINE GENERATOR**

Andrews, J. S. , and Baskin, J. M.

An extensive program of testing is described which encompasses verification of analytical procedures, component development, and integrated system verification. Objectives are to assure achievement of the 30-year design operational life as well as to minimize costly design modifications required by on-site testing. Topics discussed are computer code modifications, verification of fatigue lives of structural and dynamic components, functional checks of mechanical and electrical components and subsystems, and comparison of measured and predicted system natural frequencies. Test items include a 1/10th scale wind tunnel model, steel material for blades, crack detection system, bolted rib field joint between blades and hub, blade static buckling, blade tip spindle assembly, pitch control system, teeter bearing, rotating hydraulic reservoir, gearbox, and a modal survey of the completed wind turbine.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 219-225.

**FATIGUE LOAD SPECTRA FOR UPWIND AND DOWNWIND ROTORS**

Andrews, J. S.

Effects of both alternating and mean loads on the fatigue life of an upwind and downwind Mod-2 wind turbine system is presented. It is shown that the fatigue damage varies as the product of the stress range cubed and the maximum stress. Hence, the cyclic flapwise load caused by tower shadow and wind shear is an important factor in determining rotor blade life.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 39-52.

#### **USE OF ASYMPTOTIC METHODS IN VIBRATION ANALYSIS**

Ashley, H.

The derivation of dynamic differential equations is described, suitable for studying the vibrations of rotating, curved, slender structures. The Hamiltonian procedure is advocated for this purpose. Various reductions of the full system of equations which govern the vibrating Troposkien are displayed, derived when various order-of-magnitude restrictions are placed on important parameters.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 637-652; and Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 143-156.

#### **TEST STATUS AND EXPERIENCE WITH THE 7.5 MEGAWATT MOD-2 WIND TURBINE CLUSTER**

Axell, R. A. , and Woody, H. B.

On May 29, 1981, a ceremony was held to dedicate the 7.5-megawatt cluster of three Mod-2 HAWTs located at Goodnoe Hills, near Goldendale, Washington. This paper presents a description of the development of that cluster, including site preparation and construction activities, preliminary test results, current status, and future plans for the cluster both as a wind power plant and as a wind turbine research facility.

Proceedings, 15th Intersociety Energy Conversion Engineering Conference, 1980, Society of Automotive Engineers (Warrendale, Pennsylvania), pp. 1159-1163.

#### **THE MOD-2 WIND TURBINE**

Axell, R. A. , and Helms, P. W.

85N23242 NASA-TM-86950 DOE/NASA/20320-62, 1985.

#### **DEVELOPMENT OF LARGE, HORIZONTAL-AXIS WIND TURBINES**

Baldwin, D. H. , and Kennard, J.

A program to develop large, horizontal-axis wind turbines is discussed. The program is directed toward developing the technology for safe, reliable, environmentally acceptable large wind turbines that can generate a significant amount of electricity at costs competitive with those of conventional electricity-generating systems. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements. Several ongoing projects in large-wind-turbine development are directed toward meeting the technology requirements for utility applications. The machines based on first-generation technology (Mod-0A and Mod-1) successfully completed their planned periods of experimental operation in June, 1982. The second-generation machines (Mod-2) are in operation at selected utility sites. A third-generation machine (Mod-5) is under contract. Erection and initial operation of the Mod-5 in Hawaii should take place in 1986. Each successive generation of technology increased reliability and energy capture while reducing the cost of electricity. These advances are being made by gaining a better understanding of the system-design drivers, improving the analytical design tools, verifying design methods with operating field data, and incorporating new technology and innovative designs. Information is given on the results from the first- and second-generation machines (Mod-0A, -1, and -2), the status of the Department of Interior, and the status of the third-generation wind turbine (Mod-5).

85N30478 NASA-TM-83480 DOE/NASA/20320-52, 1983; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 11-20.

#### **THE FEDERAL WIND PROGRAM AT NASA LEWIS**

Baldwin, D. H. , and Linscott, B. S.

There are several ongoing large wind system development projects directed toward meeting the technology requirements for utility applications. The first generation technology machines, Mod-0A and Mod-1, have successfully completed their planned periods of experimental operation. Disposition of these machines is nearly complete. The second generation machines, Mod-2's, continue experimental operation at Goodnoe Hills, WA, and Medicine Bow, Wy. Design and engineering development of third generation, Mod-5, machines is underway. Initial experimental operation of Mod-5 is planned for DOE in late 1984 or early 1985. An overview of these project activities is presented. In addition to these projects, NASA also is conducting research on large horizontal axis wind turbines. The four main areas of experimental research are: (1) aerodynamics; (2) structural dynamics and aeroelasticity; (3) composite and hybrid composite materials; and (4) multiple system interaction. Key research activities and results are described. The continuing need for future wind turbine research and technology development is explored.

82N76316

**LARGE WIND TURBINE PROJECTS FOR GENERATION OF ELECTRICITY: STATUS REPORT**

Baldwin, D. H.

80A35499 and 80N23102 NASA-TM-81486; also Proceedings, 99th Meeting of Acoustical Society of America, 1980, 18 pp.

**AN EXPLORATORY SURVEY OF NOISE LEVELS ASSOCIATED WITH A 100 KW WIND TURBINE**

Balombin, J. R.

During performance tests of a 125-foot diameter, 100 kW wind turbine at the NASA Plum Brook Station near Sandusky, Ohio, the opportunity arose to make exploratory noise measurements and results of those surveys are presented. The data include measurements as functions of distance from the turbine, and directivity angle, and cover a frequency range from 1 Hz to several kHz. Potential community impact is discussed in terms of A-weighted noise levels relative to background levels, and the infrasonic spectral content. Finally, the change in the sound power spectrum associated with a change in the rotor speed is described. The acoustic impact of this size wind turbine is judged to be minimal.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 697-700.

**LIGHTNING SAFETY CONSIDERATIONS FOR WIND DRIVEN TURBINE GENERATORS**

Bankaitis, H.

This paper discusses a formal and disciplined procedure by which the hazards that naturally-occurring lightning presents to wind turbines, alone or in clusters. Issues addressed are safety of the public and site personnel, safety of hardware, and the environment. Lightning characteristics, safety concepts, probability of a strike, strike effects, experience to date, and rationale for lightning accommodation systems are all discussed.

82N23679 NASA-TM-82784 DOE/NASA/20320-37, 1982.

**EVALUATION OF LIGHTNING ACCOMMODATION SYSTEMS FOR WIND-DRIVEN TURBINE ROTORS**

Bankaitis, H.

Wind-driven turbine generators are being evaluated as an alternative source of electric energy. Areas of favorable location for the wind-driven turbines (high wind density) coincide with areas of high incidence of thunderstorm activity. These locations, coupled with the 30-m or larger diameter rotor blades, make the wind-driven turbine blades probable terminations for lightning strikes. Several candidate systems of lightning accommodation for composite-structural-material blades were designed and their effectiveness evaluated by submitting the systems to simulated lightning strikes. The test data were analyzed and system design were reviewed on the basis of the analysis.

81N24539 NASA-TM-82601 DOE/NASA/20320-31, 1980; also Proceedings, 5th International System Safety Conference, Denver, 1981.

**LIGHTNING ACCOMMODATION SYSTEMS FOR WIND TURBINE GENERATOR SAFETY**

Bankaitis, H.

The wind turbine safety program identifies the naturally occurring lightning phenomenon as a hazard with the potential to cause loss of program objectives, injure personnel, damage system instrumentation, structure or support equipment and facilities. Several candidate methods of lightning accommodation for each blade were designed, analyzed, and tested by submitting sample blade sections to simulated lightning. Lightning accommodation systems for composite blades were developed. Their effectiveness was evaluated by submitting the systems to simulated lightning strikes. The test data were analyzed and system designs were reviewed on this basis. This activity is directed at defining design and procedural constraints, requirements for safety devices, warning methods, special procedures, protective equipment and personnel training.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 159-172.

**APPROACHES TO WIND RESOURCE VERIFICATION**

Barchet, W. R.

The extent to which the regional wind energy resource assessments produced by the Pacific Northwest Laboratory are representative of actual wind conditions is addressed. Verification approaches are described, including qualitative indicators of wind speed (tree deformation, eolian features), old and new data of opportunity not at sites chosen for their exposure to the wind, and data by design from locations specifically selected to be good wind sites. Data requirements and evaluation procedures for verifying the resource are discussed.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 285-292.

#### **WTG ENERGY SYSTEMS' ROTOR -- STEEL AT 80 FEET**

Barrows, R. E.

To date, this three-bladed rotor has seen well over one million, fully reversing, maximum load fatigue cycles in the maximum stress areas with no component failure or signs of metal fatigue. Design and performance are discussed, with suggestions for future R&D requirements.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 157-174.

#### **CONTROL SYSTEM DESIGN FOR THE MOD-5A 7.3-MW WIND TURBINE GENERATOR**

Barton, R. S. , Hosp, T. J. , and Schanzenbach, G. P.

This paper provides descriptions of the requirements, analysis, hardware development, and software development phases of the control system design, which provides real-time regulation of rotor speed by control of both rotor torque and generator torque. A variable speed generator system is used, which provides the ability to control both airgap torque and reactive power. Turbine blades are designed with segmented ailerons which are positioned to control rotor torque. An orderly two-phase plan was used for controller software development, and a microcomputer-based turbine simulator was employed to facilitate hardware and software integration and testing.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 199-210.

#### **VARIABLE SPEED GENERATOR APPLICATION ON THE MOD-5A 7.3-MW WIND TURBINE**

Barton, R. S.

This paper describes the application of a Scherbiustat-type variable speed subsystem utilized for both starting assistance in a motoring mode and generation in a controlled airgap torque mode. Reactive power is also provided. The Scherbiustat-type arrangement is a wound-rotor machine with a cycloconverter in the rotor circuit, and was selected after an evaluation of the power train costs and risks of different variable-speed technologies. Evaluation factors and evaluation results are described, and operating strategies and performance simulations are summarized.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 803-820; and Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 157-168.

#### **CONCEPTUAL DESIGN OF THE 6 MW MOD-5A WIND TURBINE GENERATOR**

Barton, R. S. , and Lucas, W. C.

The conceptual design phase of the Mod-5A project is described, resulting in a 400-ft diameter, 6 MW, two-bladed, upwind HAWT with a two-speed gearbox, tip control, and wood laminate blades. The cost-of-energy requirement for this design is \$ 0.0375 per kWh (1980). In addition to a definition of the Mod-1 configuration, this paper presents operational and environmental factors that drive various portions of the design; development of weight and cost estimating models; and the use of these models in optimizing the Mod-5A to meet its COE requirement. Detailed descriptions of the major subsystems are given, in order that the results of the various trade and optimization studies can be more readily visualized.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 167-178.

#### **MOD-1 WIND TURBINE GENERATOR ANALYSIS**

Barton, R. S.

A general summary of the control system of the Mod-1 wind turbine generator and a computer simulation of this system are presented. Mechanical and speed stabilization control methods for adding damping to the drive train are mentioned, and simulation results are displayed showing the effects of speed stabilization.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 51-66.

#### **ON THE WAKE OF A DARRIEUS TURBINE**

Base, T. E. , Robertson, G. , and Nowak, E. S.

Theory and experimental measurements on the aerodynamic decay of a wake from a model Darrieus rotor (28 cm in diameter and 45.5 cm high) are discussed. Experiments showed that the rotor wake decayed at a slower rate than the wake of a screen with similar troposkein shape and drag. Initial wind tunnel test results indicate that VAWTs should be spaced at least 40 diameters apart to avoid mutual power depreciation greater than ten percent.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 215-238.

**FIBERGLASS COMPOSITE BLADES FOR THE 2 MW MOD-1 WIND TURBINE GENERATOR**

Batesole, W. R.

This paper describes in detail the design, tooling, materials, fabrication, and testing of a pair of 100-ft long blades to serve as spares for the Mod-1 wind turbine and further develop fiberglass blade technology. Structural spars were fabricated by the Transverse Filament Tape (TFT) process. Differences between these blades and an earlier 150-ft prototype blade are discussed, which were introduced for cost and manufacturing improvement purposes. The lightning protection system and its development are also described. Actual costs and work hours expended on Blade No. 2 are provided, along with cost projections for production blades of this design. Cost drivers are identified which are applicable to future designs.

NASA-CR-167987 DOE/NASA/0131-1, 1981.

**DESIGN AND FABRICATION OF COMPOSITE BLADES FOR THE MOD-1 WIND TURBINE GENERATOR**

Batesole, W. R. , and Gunsallus, C. T.

NASA-TT-F-15,356, 1974, Technical Translation.

**A WIND PLANT TO POWER SEA SIGNALS**

Baumeister, F.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 173-176.

**AN APPROXIMATE METHOD FOR SOLUTION TO VARIABLE MOMENT OF INERTIA PROBLEMS**

Beans, E. W.

The weather-vaning motion of a wind turbine with a moving rotor is an oscillatory problem with a variable moment of inertia. The analysis of such motion requires the solution of a non-linear differential equation. An approximation method is presented here for reducing the problem to an equivalent constant moment of inertia problem. An integrated average value of moment of inertia for a single rotor revolution is determined, and this averaged value can then be used to determine equivalent natural frequencies and other dynamic properties of the system.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 177-187.

**COMPUTATION OF THE MODES AND POLAR MOMENT OF INERTIA OF THE BLADES OF AN HAWT**

Beaulieu, G. , and Noiseux, D.

Numerical solution of the coupled differential equations of motion of the blades of a HAWT, considered to be more direct than the technique of finite elements, permits optimization of the blade design at relatively low cost. The procedure described consists of transforming the equation of motion into a set of first-order equations and solving them with fourth-order Runge-Kutta integrators. Application to a twisted, tapered blade of variable cross section and stiffness is given, and the first six natural frequencies and mode shapes are obtained. A good match with experimental results is obtained.

NASA-CR-165566 DOE/NASA/0182-1, 1982.

**FATIGUE TESTING OF LOW-COST FIBERGLASS COMPOSITE WIND TURBINE BLADE MATERIAL**

Bennett, L. C. , and Hofer, K. E.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 41-45.

**WIND POWER DEMONSTRATION AND SITING PROBLEMS**

Bergey, K. H.

**83N19256** Proceedings, Large Horizontal-Axis Wind Turbine Conference, 1981, NASA CP-2230, DOE CONF-810752, pp. 469-490.

**OPERATING EXPERIENCE WITH FOUR 200 KW MOD-0A WIND TURBINE GENERATORS**

Birchenough, A. G. , Saunders, A. L. , Nyland, T. W. , and Shaltens, R. K.

Field test results obtained with four units of the 38-m diameter experimental wind-powered generator, designated as the Mod-0A, and described. The advantages and disadvantages of the design, particularly as these affect reliability, are discussed. Machine performance data with regard to power availability and power output are also given.

83N15916 Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, National Renewable Energy Laboratory (Golden, Colorado), pp. 107-118.

**OPERATING EXPERIENCE WITH THE 200 KW MOD-0A WIND TURBINE GENERATORS**

Birchenough, A. G. , Saunders, A. L. , Nyland, T. W. , and Shaltens, R. K.

The machine configuration and its advantages and disadvantages, particularly as it affects reliability are discussed. The machine performance, both availability and power output characteristics are described. The Mod-0A operational experience is documented. The characteristics of the wind energy generated, the machine performance, and the subsystem strengths and weaknesses are discussed. An assessment of the project success in fulfilling its goals and objectives is also presented.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 175-184.

**USE OF BLADE PITCH CONTROL TO PROVIDE POWER TRAIN DAMPING THE MOD-2 2.5-MW WIND TURBINE**

Blissell, W. A.

The control system of the Mod-2 HAWT is described, which provides not only for startup, rotor speed regulation, maximizing or regulating power, and stopping the rotor, but also for load limiting, especially of torques in the power train. Early operations in above-rated winds revealed an instability which was caused primarily by coupling between the drive train and the rotor air loads. The first of several major Mod-2 control system changes, to correct this instability, are reviewed in the paper.

NASA-CR-180896 DOE/NASA/0200-3, 1988.

**MOD-5B WIND TURBINE SYSTEM FINAL REPORT -- VOLUME I: EXECUTIVE SUMMARY**

Boeing Aerospace Company

NASA-CR-174989 DOE/NASA.0002-85/1, 1985.

**MOD-2 WIND TURBINE CLUSTER GOODNOE HILLS OPERATION, OCTOBER 1982 - APRIL 1985**

Boeing Aerospace Company

EPRI Report AP-4060, Project 1996-6, 1985, Electric Power Research Institute (Palo Alto, California).

**GOODNOE HILLS MOD-2 CLUSTER TEST PROGRAM -- VOLUMES 1 AND 3**

Boeing Aerospace Company

NASA-CR-168006, 1982.

**MOD-2 WIND TURBINE SYSTEM DEVELOPMENT FINAL REPORT -- VOLUME 1: EXECUTIVE SUMMARY**

Boeing Aerospace Company

NASA-CR-168007, 1982.

**MOD-2 WIND TURBINE SYSTEM DEVELOPMENT FINAL REPORT -- VOLUME 2: DETAILED REPORT**

Boeing Aerospace Company

NASA-CR-168046 DOE/NASA/0200-1, 1982.

**MOD-5B WIND TURBINE SYSTEM CONCEPT AND PRELIMINARY DESIGN REPORT -- VOLUME I: EXECUTIVE SUMMARY**

Boeing Engineering and Construction Company

NASA-CR-168047 DOE/NASA/0200-2, 1982.

**MOD-5B WIND TURBINE SYSTEM CONCEPT AND PRELIMINARY DESIGN REPORT -- VOLUME II: DETAILED REPORT**

Boeing Engineering and Construction Company

NASA-CR-159609 DOE/NASA/0002-80/1 and -80/2, 1979.

**MOD-2 WIND TURBINE SYSTEM CONCEPTS AND PRELIMINARY DESIGN REPORT -- VOLUME I: EXECUTIVE SUMMARY; VOLUME II: DETAILED REPORT**

Boeing Aerospace Company

DOE/BP-653 Report, 1986, Bonneville Power Administration (Portland, Oregon).

**THE WORLD'S FIRST MULTI-MEGAWATT WIND FARM -- CONSTRUCTION OF THE MOD-2 WIND TURBINE GENERATORS AT GOODNOE HILLS, WASHINGTON, TO EVALUATE A NEW SOURCE OF RENEWABLE ENERGY**

Bonneville Power Administration

DOE/BP-85 Report, 1981, Bonneville Power Administration (Portland, Oregon).

**BUILDING THE WORLD'S FIRST WIND FARM**

Bonneville Power Administration

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 271-275.

**PASSIVE CYCLIC PITCH CONTROL FOR HORIZONTAL AXIS WIND TURBINES**

Bottrell, G. W.

A new flexible rotor concept, called the balanced-pitch rotor, is described. The system provides passive adjustment of cyclic pitch in response to unbalanced pitching moments across the rotor disk. Various applications are described and performance predictions are made for wind shear and cross-wind operating conditions. Comparisons with the teetered hub are made and significant cost savings are predicted.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 158-163.

**THE EVOLUTION OF THE MOD-2 AND MOD-5B WIND TURBINE SYSTEMS**

Bovarnick, M. L. , and Engle, W. W.

This paper briefly describes the development of the 2.5-MW Mod-2 HAWT design, experience with five prototype units, and how this experience has benefitted the design of the third-generation 3.2-MW Mod-5B. Mod-2 operating hours to date are over 14,000, which is less than expected because of design problem that are now resolved. Major performance improvements have been incorporated into the Mod-5B design and a prototype unit will be installed on Oahu in the Hawaiian Islands in 1986. Lessons learned with the Mod-2 machines are discussed.

86N16487 NASA-TM-87181 DOE/NASA/20320-67, 1985.

**DESCRIPTION AND TEST RESULTS OF A VARIABLE SPEED, CONSTANT FREQUENCY GENERATING SYSTEM**

Brady, F. J.

This paper presents the results of laboratory tests on a system consisting of a 250 hp wound-rotor machine and a 12-pulse cycloconverter to evaluate performance prior to installation in the Mod-0 experimental HAWT. All testing was done with the stator of the generator connected to the utility network and with the rotor fed through the cycloconverter. Characteristics such as power regulation, transient response, harmonic content, and efficiency were determined. Operation was found to be stable over a useful speed range, the generator stayed synchronized to the network while experiencing variations in shaft speed, and the cycloconverter operated reliably through the zero-slip speed and into the super-synchronous range. This report describes the system as it existed at the conclusion of the project. The cycloconverter control circuit is described including the addition of field-oriented control. In addition to laboratory test data, actual wind turbine test results are included.

NASA-TM-83454 DOE/NASA/20305-9, 1983.

**A MATHEMATICAL MODEL FOR THE DOUBLE-FED WOUND ROTOR GENERATOR**

Brady, F. J.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 287-293.

**MOD-0 WIND TURBINE DYNAMICS TEST CORRELATIONS**

Brooks, B. M.

The behavior of the teetered, downwind, free yaw, Mod-0 wind turbine, as represented by NASA dynamic test data, was used to support confidence in simulations of megawatt-scale HAWTs performed with the Hamilton Standard F762 computer code. Trim position, performance at trim, and teeter response as predicted by the computer code were compared to test results. Several new test configurations are recommended for exploring free-yaw behavior. It is shown that eliminating rotor tilt and optimizing coning and blade twist can contribute to good free-yaw behavior and stability. Effects of rotor teeter, teeter gravity balance, inflow, and other physical and operating parameters were also investigated analytically using the F762 code.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 151-154.

#### **THE HYDRAULIC WINDMILL**

Browning, F. A.

An hydraulic windmill is described, in which a 71-ft diameter rotor drives a pump atop the tower sending pressurized oil from rotor shaft level to the ground where an hydraulic motor-generator set produces electricity. Alternatively, the useful output may be heat. Rotor speed is governed by a flow valve. Over-pressure, the result of high wind velocity, rotates the tail to move the rotor blades out of the wind. Loss of oil pressure causes a brake to close as well as to swing the tail to its maximum distance from the rotor plane.

PNL-5565 Report, 1985, Pacific Northwest Laboratories (Richland, Washington)

#### **OBSERVATIONS OF WAKE CHARACTERISTICS AT THE GOODNOE HILLS MOD-2 ARRAY**

Buck, J. W. , and Renné, D. S.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 204-205.

#### **A COMMENT ON TOWERS FOR WINDMILLS**

Budgen, H. P.

NASA-CR-168108 DOE/NASA/3303-1, 1981.

#### **SOME EXPERIMENTS ON YAW STABILITY OF WIND TURBINES WITH VARIOUS CONING ANGLES**

Bundas, D. , and Dugundji, J.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 259-266.

#### **FIBERGLASS COMPOSITE BLADES FOR THE 4 MW WTS-4 WIND TURBINE**

Bussolari, R. J.

This paper describes the design and fabrication of fiberglass blades each 38 m long. Blade configuration is a two-cell, monolithic structure of filament-wound fiberglass/epoxy composite with non-linear taper and twist. Hub retention design provides redundancy for durability and safety. Advanced tooling is described in which a sophisticated computer control and a sequence of manufacturing steps are used to achieve the unique filament-wound airfoil shape.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 675-687; and Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 183-192.

#### **STATUS OF THE 4 MW WTS-4 WIND TURBINE**

Bussolari, R. J.

The specifications, characteristics, and features of the WTS-4, a 78.1-m two-bladed HAWT rated at 4 MW, are discussed. Presently under fabrication, this turbine will be installed near Medicine Bow, Wyoming, for the U.S. Department of the Interior as a system verification unit for the integration of wind power with hydropower. Major components (rotor, nacelle, tower, etc.) are described and the fabrication status of each is presented.

NASA-TM-73835 DOE/NASA/1028-77/13, 1978.

#### **WIND TURBINE GENERATOR ROTOR BLADE CONCEPTS WITH LOW COST POTENTIAL**

Cahill, T. P. , and Sullivan, T. L.

WER-32A, 1987, Wichita State University (Wichita, Kansas).

#### **SUMMARY OF CONTROL EFFECTIVENESS OF VENTED DEFLECTOR-AILERONS**

Cao, H. V. , Wentz, W. H. Jr. , and Snyder, M. H.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 255-264.

#### **GUY CABLE DESIGN AND DAMPING FOR VERTICAL AXIS WIND TURBINES**

Carne, T. G.

The axial load which the guy cables on a VAWT apply to the tower, bearings, and foundations is an undesirable consequence of using guys to support the turbine. Limiting the axial load so that it does not significantly affect the cost of the turbine is an important objective of cable design and this investigation. Lateral vibrations of the cables are another feature

of cable design considered here, and a technique for damping cable vibrations is analyzed mathematically and demonstrated experimentally.

NASA-CR-2540, 1975.

**WIND-TUNNEL MEASUREMENTS IN THE WAKE OF A SIMPLE STRUCTURE IN A SIMULATED ATMOSPHERIC FLOW**

Cermak, J. E. , Peterka, J. A. , and Hansen, A. C.

**78N12459** ERDA/NASA/1004-77/4, 1977; also Proceedings, 6th NASTRAN Users' Colloquium, 1978, NASA (Washington, DC), pp. 213-233.

**NASTRAN USE FOR CYCLIC RESPONSE AND FATIGUE ANALYSIS OF WIND TURBINE TOWERS**

Chamis, C. C. , Manos, P. , Sinclair, J. H. , and Winemiller, J. R.

A procedure is described which uses NASTRAN coupled with fatigue criteria via a post-processor to determine the cyclic response and to assess the fatigue resistance (fatigue life) of wind turbine generator towers. The cyclic loads to which the tower may be subjected are entered either in a quasi-static approach through static load sub-cases (Rigid Format 1) or through the direct dynamic response (Rigid Format 9) features of NASTRAN. The fatigue criteria are applied to NASTRAN output data from either rigid format through an externally written user program embedded in a post-processor.

**76A28027** and **76N18674** NASA-TM-X-71879 ERDA/NASA/1028-77/7, 1976; also Proceedings, Specialty Conference on the Dynamic Response of Structures, 1976, American Society of Civil Engineers, 16 p.

**FREE VIBRATIONS OF THE ERDA-NASA 100-kW WIND TURBINE**

Chamis, C. C. , and Sullivan, T. L.

The ERDA-NASA wind turbine (windmill), which consists of a 93-foot truss tower, a bed plate that supports mechanical and electrical equipment, and two 62.5-foot long blades, was analyzed to determine its free vibrations using NASTRAN. The finite element representation of the system consisted of beam and plate elements. The free vibrations of the tower alone, the blades alone, and the complete system were determined experimentally in the field. These results were obtained by instrumenting the tower or blades with an accelerometer and impacting the components with an instrumented mass. The predicted results for natural frequencies and mode shapes were in excellent agreement with measured data.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 107-108.

**BUCKET ROTOR WIND-DRIVEN GENERATOR**

Chang, H. H. , and McCracken, H.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 237-242.

**COMPARISON OF BLADE LOADS OF FIXED AND FREE YAWING WIND TURBINES**

Cheney, M. C. , and Bielawa R. L.

The UTRC (United Technology Research Center) Composite Bearingless wind Turbine utilizes an automatic pitch control concept and a completely unrestrained yawing degree of freedom. Aerodynamic moments caused by skewed flow provide the control to align the wind turbine with the wind. Model tests have demonstrated the feasibility of the concept and analytical studies have shown the free system to experience lower blade loads compared to the fixed system.

NASA-CR-134956 ERDA/NASA/9235-75/1, 1975.

**100-kW METAL TURBINE BLADE BASIC DATA, LOADS, AND STRESS ANALYSIS**

Cherrett, A. W. , and Gaidelis, J. A.

NASA-CR-165589 DOE/NASA/1900-1, 1982.

**VIBRATION ANALYSIS OF THREE GUYED TOWER DESIGNS FOR INTERMEDIATE SIZE WIND TURBINES**

Christie, R. J.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 305-314.

**VERTICAL AXIS WIND TURBINE DRIVE TRAIN TRANSIENT DYNAMICS**

Clauss, D. B. , and Carne, T. G.

Start-up of a VAWT causes transient torque oscillations in the drive train with peak torques which may be over two and one-half times the rated torque, so mechanical components must be over-designed for safety and reliability. A computer code is described, based on a lumped parameter model of the drive train, and calculated transient torques are compared to torques measured on the Low Cost 17-m VAWT. Excellent agreement was obtained. It has been demonstrated that a slip clutch located between the starting motor and rotor brake can reduce peak torques by almost 40 percent.

Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 165-169.

#### **WIND POWER SYSTEMS FOR INDIVIDUAL APPLICATIONS**

Clews, H. M.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 71-76.

#### **FLOW FIELD ANALYSIS**

Cliff, W. C. , and Verholek, M. G.

The average mean wind speed integrated over a disk is shown to be extremely close to the mean value of wind speed which would be measured at the center of a disk for most site geometries in which a WECS would operate. Field test results are presented which compare instantaneous records of wind speed integrated over a disk with the wind speed measured at the center of the disk. The wind field that a rotating element would experience is presented which has been synthesized from the outputs of an array of anemometers.

83N19257 and 82N30710 NASA-TM-82721 DOE/NASA/20366-2, 1982; also Proceedings, Large Horizontal-Axis Wind Turbine Conference, 1981, NASA CP-2230, pp. 491-574.

#### **EXPERIENCE AND ASSESSMENT OF THE DOE/NASA MOD-1 2000 KW WIND TURBINE GENERATOR AT BOONE, NORTH CAROLINA**

Collins, J. L. , Shaltens, R. K. , Poor, R. H. , and Barton, R. S.

This paper presents an extensive review of the Mod-1 project, which developed megawatt-scale wind turbine technology in the U.S. for the first time in almost 40 years following the historic Smith-Putnam project. Mod-1 program objectives are defined and the Mod-1 wind turbine design and test operations are described in detail. In addition to the steel blade operated on the wind turbine, a composite blade was designed and manufactured. During the early phase of the manufacturing cycle of Mod-1A configuration was designed that identified concepts such as partial span control, a soft tower, and upwind teetered rotors that were incorporated in second and third generation industry designs. The Mod 1 electrical system performed as designed, with voltage flicker characteristics within acceptable utility limits. Power output versus wind speed equaled or exceeded design predictions. The wind turbine control system was operated successfully at the site and remotely from the utility dispatcher's office. During wind turbine operations, television interference was experienced by the local residents. As a consequence, operations were restricted. Although not implemented, two potential solutions were identified. In addition to television interference, a few local residents complained about objectionable sound, particularly the 'thump' as the blade passed behind the tower. To eliminate objections, the sound generation level was reduced by 10 dB by reducing the rotor speed from 35 rpm to 23 rpm. Bolts in the drive train fractured. A solution was identified but not implemented. The public reaction toward the Mod 1 wind turbine program was overwhelmingly favorable.

Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 125-142.

#### **EXPERIENCE AND ASSESSMENT OF THE DOE/NASA MOD-1 2000 KW WIND TURBINE GENERATOR AT BOONE, NORTH CAROLINA**

Collins, J. L. , and Poor, R. H.

Project activities began in 1974 and dedication of the 200-ft diameter Mod-1 HAWT with its downwind, two-bladed, rigid hub rotor occurred in July 1979. Rated power generation was accomplished in February 1980, with the electrical system performing as designed within acceptable utility limits. Subjects summarized in this paper are power output versus wind speed, control system operation, TV interference, noise, and overall public reaction which has been favorable.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 1 - 16.

#### **BASIC PRINCIPLES AND RECENT OBSERVATIONS OF ROTATIONALLY-SAMPLED WIND**

Connell, J. R.

The concept of rotationally-sampled wind speed is described, and quantitative characterization is made in terms of a

power spectral density function verified by wind spectra measured at the Mod-0A vertical-plane array of anemometers at Clayton, New Mexico. Rotational wind speed measurements made with hot-film anemometers attached to rotating blades are compared with theoretical predictions. The importance of temperature layering and complex terrain is demonstrated with hot-film, meteorological tower, and acoustic-Doppler sounder data from the Mod-2 site near Goldendale, Washington.

EPRI-AP-4335 Report, 1985, Electric Power Research Institute (Palo Alto, California).

**ROTATIONALLY SAMPLED WIND AND MOD-2 WIND TURBINE RESPONSE**

Connell, J. R. , *et al.*

PNL-5238 Report, 1984, Pacific Northwest Laboratories.

**ROTATIONALLY SAMPLED WIND CHARACTERISTICS AND CORRELATIONS WITH MOD-0A WIND TURBINE RESPONSE**

Connell, J. R. , and George, R. L.

PNL Report RP 1996-12, 1983, Pacific Northwest Laboratories (Richland, Washington).

**ROTATIONALLY SAMPLED WIND AND WIND TURBINE RESPONSE AT GOODNOE HILLS, MOD-2 UNIT NO. 2: PRELIMINARY ANALYSIS**

Connell, J. R. , George, R. L. , and Sandborn, V. A.

PNL-4210 Report, 1982, Pacific Northwest Laboratories (Richland, Washington).

**THE WAKE OF THE MOD-0A1 WIND TURBINE AT TWO ROTOR DIAMETERS DOWNWIND ON DECEMBER 3, 1981**

Connell, J. R. , and George, R. L.

87N29956 NASA-TM-100136 DOE/NASA/20320-73

**PERFORMANCE AND POWER REGULATION CHARACTERISTICS OF TWO AILERON-CONTROLLED ROTORS AND A PITCHABLE TIP-CONTROLLED ROTOR ON THE MOD-0 TURBINE**

Corrigan, R. D. , Ensworth, C. B. F. III , and Miller, D. R.

Tests were conducted on the DOE/NASA Mod-0 horizontal axis wind turbine to compare and evaluate the performance and the power regulation characteristics of two aileron-controlled rotors and a pitchable tip-controlled rotor. The two aileron-controlled rotor configurations used 20 and 38 percent chord ailerons, while the tip-controlled rotor had a pitchable blade tip. The ability of the control surfaces to regulate power was determined by measuring the change in power caused by an incremental change in the deflection angle of the control surface. The data shows that the change in power per degree of deflection angle for the tip-controlled rotor was four times the corresponding value for the 2- percent chord ailerons. The root mean square power deviation about a power setpoint was highest for the 20 percent chord aileron, and lowest for the 38 percent chord aileron.

86N30251 NASA-TM-88810 DOE/NASA-20320/70, 1986; also Proceedings, Energy Sources Technology Conference and Exhibition, 1986, American Society of Mechanical Engineers (New York).

**DESIGN AND INITIAL TESTING OF A ONE-BLADED 30-METER-DIAMETER ROTOR ON THE NASA/DOE MOD-0 WIND TURBINE**

Corrigan, R. D. , and Ensworth, C. B. F. III

The concept of a one-bladed horizontal-axis wind turbine has been of interest to wind turbine designers for many years. Many designs and economic analyses of one-bladed wind turbines have been undertaken by both United States and European wind energy groups. The analyses indicate significant economic advantages but at the same time, significant dynamic response concerns. In an effort to develop a broad data base on wind turbine design and operations, the NASA Wind Energy Project Office has tested a one-bladed rotor at the NASA/DOE Mod-0 Wind Turbine Facility. This is the only known test on an intermediate-sized one-bladed rotor in the United States. The 15.2-meter-radius rotor consists of a tip-controlled blade and a counterweight assembly. A rigorous test series was conducted in the fall of 1985 to collect data on rotor performance, drive train/generator dynamics, structural dynamics, and structural loads. This report includes background information on one-bladed rotor concepts, and Mod-0 one-bladed rotor test configuration, supporting design analysis, the Mod-0 one-blade rotor test plan, and preliminary test results.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 483-490.

#### **THE NASA TEST PROGRAM FOR A 15 METER RADIUS ONE-BLADED ROTOR**

Corrigan, R. D. , Ensworth, C. B. F. III , and Sirocky, P. J.

This is a preliminary report on the development of a one-bladed rotor for the 100-kW Mod-0 experimental HAWT and the tests planned for this configuration. Background information on one-bladed rotor concepts, a description of the hardware, and supporting loads and performance analyses are given.

**86A24920** Proceedings, 20th Intersociety Energy Conversion Engineering Conference, Volume 3, 1985, Society of Automotive Engineers (Warrendale, Pennsylvania), pp. 3.663-3.668.

#### **VORTEX GENERATORS AS A MEANS FOR INCREASING ROTOR PERFORMANCE**

Corrigan, R. D. , and Savino, J. M.

Field tests on a horizontal axis wind turbine (HAWT) have shown that vortex generators (VGs) can increase the efficiency of large propeller type (horizontal axis) wind turbines. VGs are devices which are attached to the surfaces of an aerodynamic body to influence the boundary layer behavior. It is pointed out that VGs were originally developed for delaying stall on aircraft wings. An investigation was conducted regarding the possibility to employ Vgs also for the improvement of the performance of an intermediate size HAWT with a diameter in the range from 24 to 46 meters. This investigation included wind tunnel tests involving a rotor blade tip section, and field tests. The wind tunnel tests showed that VGs can improve the peak lift capabilities of the section while only slightly increasing the drag. The field tests showed that VGs can increase the rotor power in winds above 6 m/s.

**85N30477** NASA-TM-83471 DOE/NASA/20320-51, 1985; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 427-436.

#### **PERFORMANCE COMPARISON BETWEEN NACA 23024 AND NACA 64(3)-618 AIRFOIL CONFIGURED ROTORS FOR HORIZONTAL-AXIS WIND TURBINES**

Corrigan, R. D. , Ensworth, C. B. F. III , and Keith, T. G. Jr.

Wind turbine performance tests were conducted on the Mod-0 100-kW horizontal-axis wind turbine to compare a tip-controlled rotor having NACA 23024 airfoil tip sections with a similar rotor having NACA 64<sub>3</sub>-618 airfoil tip sections. The inboard portion of the blades had an NACA 23024 airfoil section. The wind turbine configuration consisted of the nacelle-rotor assembly mounted atop a tubular tower with the rotor axis 38 m above ground level. The rotor was 39 m in diameter, coned, and teetered and had 20 deg of pitch and flap coupling delta sub 3. The blades had 23 percent root cutout and the movable tip-control section covered the outer 31 percent of the blade. Testing was conducted at nominal rotor speeds of 20 and 31 rpm with the rotor downwind of the tower. The tests indicate improved performance for the rotor with the NACA 64<sub>3</sub>-618 airfoil tip sections over the rotor with the NACA 23024 airfoil tip sections. In addition, performance was predicted for each rotor configuration by using two performance prediction codes. This report presents the test results and compares them with each other and with predicted performance for both rotor configurations.

**85N27385** NASA-TM-86986 DOE/NASA/20320-64, 1985; also Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), pp. 69-76.

#### **EFFECT OF PRECIPITATION ON WIND TURBINE PERFORMANCE**

Corrigan, R. D. , and Demiglio, R. D.

The effects of precipitation on wind turbine power output were measured and an analytical model was developed. The tests were conducted on the 125-ft diameter two-bladed Mod-0 experimental HAWT with three different rotor configurations. Experimental data from these tests are presented which clearly indicate that the performance of the Mod-0 wind turbine is affected by rain. Light rainfall degraded performance by as much as 20 percent while heavy rainfall degraded performance by as much as 30 percent. Snow mixed with drizzle degraded performance by as much as 36 percent at low wind speeds. Also presented are the results of an analysis to predict the effect of rain on wind turbine performance. This analysis used a blade element/momentum code with modified airfoil characteristics to account for the effect of rain and predicted a loss in performance of 31 percent in high winds with moderate rainfall rates. These predicted results agreed well with experimental data.

**83N19235** Proceedings, Large Horizontal-Axis Wind Turbine Conference, 1981, NASA CP-2230, DOE CONF-810752, pp. 103-124.

#### **FREE YAW PERFORMANCE OF THE MOD-0 LARGE HORIZONTAL AXIS 100 KW WIND TURBINE**

Corrigan, R. D. , and Viterna, L. A.

The NASA Mod-0 large horizontal axis, 100-kW wind turbine was operated in free yaw with an unconed teetered, downwind rotor mounted on a nacelle having 8-1/2 deg tilt. Two series of tests were run, the first series with 19-meter twisted aluminum blades and the second series with 19-meter untwisted steel spar blades with tip control. Rotor speed were nominally 20, 26 and 31 rpm. It was found the nacelle stabilized in free yaw at a yaw angle of between -55 deg to -45 deg was relatively independent of wind speed and was well damped to short term variations in wind direction. Power output of the wind turbine in free yaw, aligned at a large yaw angle, was considerably less than that if the wind turbine were aligned with the wind. For the Mod-0 wind turbine at 26 rpm, the MOSTAB computer code calculations of the free yaw alignment angle and power output compare reasonably well with experimental data. MOSTAB calculations indicate that elimination of tilt and adding coning will improve wind turbine alignment with the wind and that wind shear has a slight detrimental effect on the free yaw alignment angle.

83N14689 NASA-TM-82870 DOE/NASA/20320-40, 1982; also, Proceedings, Wind and Solar Energy Conference, 1982, Kansas City, Missouri.

#### **MEASURED PERFORMANCE OF A TIP-CONTROLLED, TEETERED ROTOR WITH AN NACA 64<sub>3</sub>-618 TIP AIRFOIL**

Corrigan, R. D. , Glasgow, J. C. , and Sirocky, P. J.

Tests were conducted on the Mod-0 100 Kw Wind Turbine to determine the performance of a tip-controlled rotor having an NACA 64<sub>3</sub>-618 airfoil over the moveable outboard 30% of the blade, while operating at nominal rotor speeds of 21 and 31 rpm. Tests were conducted at two rotor speeds to assess the performance improvement which could be realized with 2-speed operation. Test data are compared with analytical predictions and concluding remarks are presented. The results indicate a clear performance improvement for the 2-speed operation.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 193-204.

#### **FABRICATION OF EXTRUDED VERTICAL AXIS TURBINE BLADES**

Craig, A. G. Jr.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 265-268.

#### **THE UMASS WIND FURNACE BLADE DESIGN**

Cromack, D. E.

A brief description of a simple heating system consisting of a wind turbine, solar flat plate collectors, a storage system, and a heat delivery system is presented, along with some preliminary performance test data. Particular emphasis is placed on the design, construction and manufacturing procedure (with 8 photographs) for the 32.5-foot diameter GRP blades.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 265-270.

#### **NORTH WIND 4 KW "PASSIVE" CONTROL SYSTEM DESIGN**

Currin, H.

An overview is presented of a mechanical rotor control design in which operation at constant RPM and rapid response are obtained by using blade pitch moments for both sensing control needs and actuating blade pitch changes. The basic concept, static or equilibrium design, and dynamic analysis are briefly discussed.

78N16434 NASA-TM-73754 ERDA/NASA-1028-77/12, 1977.

#### **APPROXIMATE METHOD FOR CALCULATING FREE VIBRATIONS OF A LARGE-WIND-TURBINE TOWER STRUCTURE**

Das, S. C. , and Linscott, B. S.

A set of ordinary differential equations were derived for a simplified structural dynamic lumped-mass model of a typical large-wind-turbine tower structure. Dunkerley's equation was used to arrive at a solution for the fundamental natural frequencies of the tower in bending and torsion. The ERDA-NASA 100-kW wind turbine tower structure was modeled, and the fundamental frequencies were determined by the simplified method described. The approximate fundamental natural frequencies for the tower agree within 18 percent with test data and predictions analyzed.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111, pp. 343-354.

#### **THE BOEING MOD-2 WIND TURBINE SYSTEM ROTOR**

Davison, G. N.

The final design stage of the Mod-2 rotor was based on several very important trade studies described earlier (see paper by R. Douglas at same Conference). This discussion includes the design details, significance of fatigue strength, design development test results, and conclusions of the preliminary design efforts.

NASA-CR-174713 DOE/NASA/0260-1, 1984.

#### **DESIGN OF AN ADVANCED WOOD COMPOSITE ROTOR AND DEVELOPMENT OF WOOD COMPOSITE BLADE TECHNOLOGY**

Dechow, C. , Zuteck, M. , and Stroebel, T.

Proceedings, Wind Energy Expo '83 and National Conference, 1983, American Wind Energy Association  
(Washington, DC), pp. 48-62.

#### **STATUS UPDATE OF THE MOD-5A WIND TURBINE PROGRAM**

DiGiovacchino, D. J.

The current status of the development of this 400-ft diameter, 7.3-MW HAWT is discussed. Design activities, started in July 1980, are federally funded, and the General Electric Company is planning a prototype phase with up to 3 machines to permit a comprehensive evaluation. GE, EPRI, and the participating "user" will sponsor these hardware, test, and evaluation efforts. In June 1983, the Hawaiian Electric Company contracted with GE for the purchase of the first Mod-5A, for installation near Kahuku on the north shore of the island of Oahu, with operation planned for 1985.

Proceedings, Wind Energy Expo '82 and National Conference, 1982, American Wind Energy Association  
(Washington, DC), pp. 38-41.

#### **STATUS OF THE MOD-5A WIND TURBINE PROGRAM**

DiGiovacchino, D. J.

The design of this third-generation, megawatt-scale HAWT is described. With its 400-ft, two-bladed, wood-composite, tip-controlled rotor and rating of 7.3-MW, this turbine is designed to produce over 20 GWh per year at a 14 mph site. The gearbox provides two operating speeds, and the tower is 236 ft tall. Initially funded by the federal government, large-scale private financing is now required to construct the Mod-5A.

HSE-10804, 1986, Hamilton Standard Division (Windsor Locks, Connecticut).

#### **AN INVESTIGATION OF THE FEASIBILITY OF CONVERTING THE WTS-4 TO FIXED PITCH, BROAD RANGE VARIABLE SPEED OPERATION**

DiValentin, E. , Healy, H. , Kos, J. M. , and Stoltze, C. L.

Chapter 3 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

#### **EVOLUTION OF MODERN WIND TURBINES**

Divone, L. V.

The evolution of wind turbine technology in the United States and elsewhere since World War II is described, along with some of the problems that have arisen and how these problems have been faced.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation  
(Washington, DC), pp. 5-11 and 509-513.

#### **OVERVIEW OF WECS PROGRAM AND FUTURE FEDERAL PLANS**

Divone, L. V.

**76A28250** Proceedings, Workshop on Advanced Wind Energy Systems, Volume 2, 1974, National Swedish Board for Technical Development and Swedish State Power Board (Stockholm), pp. 7-25 to 7-33.

#### **THE U.S.-NSF/NASA WIND ENERGY CONVERSION SYSTEMS (WECS) PROGRAM**

Divone, L. V. , and Savino, J. M.

The five-year research and development plan of the NSF/NASA Wind Energy Conversion Systems (WECS) program is outlined. The program includes mission studies to determine energy use patterns and requirements and define specific applications for wind energy systems, wind energy resource assessment and development, and development of cost-effective

components and subsystems. The program is also directed towards the development of energy storage systems to make wind powered systems firm power sources where appropriate. A 100 kW experimental wind generator (Model-0) is being designed as a flexible test bed for a variety of system components. Designs will be developed for units in the 50 to 200 kW and 500 to 3,000 kW size ranges.

NASA-CR-168229 DOE/NASA/0007-1, 1983.

#### **HOW TO PROTECT WIND TURBINES FROM LIGHTNING**

Dodd, C. W. , McCalla, T. M. Jr. , and Smith, J. G.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 170-173.

#### **ECONOMIC CONSIDERATIONS OF UTILIZING SMALL WIND GENERATORS**

Dodge, R.

Chapter 10 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

#### **STRUCTURAL DYNAMIC CONSIDERATIONS IN WIND TURBINE DESIGN**

Doman, G. S.

Emphasis is placed on structural system design philosophy and, in particular, on system architectures based on compliance with the forces of nature, rather than resistance to these forces. Through the use of known analysis methods, the effects of physical changes, controls, and subsystem features on the dynamic behavior of a new or existing wind turbine can be understood.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 177-182.

#### **APPLICATION OF BROAD RANGE VARIABLE SPEED GENERATORS TO LARGE HORIZONTAL AXIS WIND TURBINES**

Doman, G. S.

The essentials of a fully-effective application of variable speed in wind turbines are described and discussed in comparison to a conventional constant-speed system. Emphasis is given to the changes of design-driving loads and in system control strategy. New structural dynamic issues are described. All these aspects of system integration are examined for feasibility at the present state of the art. Also discussed are reasons why suitable variable-speed control concepts open the way for conversion to a fixed-pitch yaw-controlled rotor system. Results of an example studied, based on the 4-MW WTS-4 HAWT, show an increase of 28% in energy capture, and a still-greater reduction in cost of energy by down-sizing torque- and thrust- loaded elements. Estimates of 20% reduction in COE for a variable-pitch system and 40% reduction for a fixed-pitch system are given when broad range variable speed operation is used.

Proceedings, Wind Energy Expo '84 and National Conference, 1984, American Wind Energy Association (Washington, DC), pp. 24-36.

#### **PERSPECTIVES ON LARGE WIND SYSTEM DEVELOPMENT**

Doman, G. S.

Topics discussed are experience to date with the WTS-3 and WTS-4 3-MW and 4-MW, respectively, HAWTs; design approach; major component stress, predicted vs measurement; 1983 recommendations; 1984 structural/control dynamics research; Medicine Bow research test program on the WTS-4; fixed-pitch/yaw-controlled conversion of the WTS-4; broad-range variable-speed conversion; why the WTS-4 can operate as a fixed-pitch/yaw-controlled system over a wide shaft speed range; and concluding perspectives.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 385-396.

#### **SYSTEM CONFIGURATION IMPROVEMENT**

Doman, G. S.

The design of a wind turbine generator is a very complex process because of the many (and often conflicting) choices and considerations involved. This paper presents the results of intensive studies into governing factors, illustrating by tangible examples a recommended approach to configuration design. Subjects included are the choice of configuration; basic configuration trade-offs in system dynamics; form of blade articulation; nacelle and tower loads reduction; soft versus stiff design concepts; fixed versus variable blade pitch; yaw control versus yaw freedom; heading trim and stability for free-yaw

systems; control of static and transient thrust loads; assurance of good system damping; and attaining unlimited fatigue life.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 256-260.

**THE STRUCTURAL AND DYNAMIC LIMITS UPON THE SIZE OF VERY LARGE ROTORS FOR WIND ENERGY CONVERSION SYSTEMS**

Doman, G. S.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 239-265.

**EVALUATION OF AN OPERATING MOD-0A 200 KW WIND TURBINE BLADE**

Donham, R. E.

Comparisons of observed and design loads and durability are presented for a 62.5-ft aluminum blades manufactured according to aircraft spar-structural skin methods. Modifications to the root region connecting the blades to the hingeless hub, where extensive cracking occurred, are described.

**76A14623** Proceedings, 31st Annual National Forum, 1975, American Helicopter Society (Washington, DC), 13 p.

**100-KW HINGELESS METAL WIND TURBINE BLADE DESIGN, ANALYSIS AND FABRICATION**

Donham, R. E. , Schmidt, J. , and Linscott, B. S.

The design, fabrication and analysis of aluminum wind turbine rotor blades is discussed. The blades are designed to meet criteria established for a 100-kilowatt wind turbine generator operating between 8 and 60-mile-per-hour speeds at 40 revolutions per minute. The design wind speed is 18 miles per hour. Two rotor blades are used on a new facility which includes a hingeless hub and its shaft, gearbox, generator and tower. Experience shows that, for stopped rotors, safe wind speeds are strongly dependent on blade torsional and bending rigidities which the basic D-spar structural blade design provides. The 0.25-inch-thick nose skin is brake/bump formed to provide the basic 'D' spar structure for the tapered, twisted blades. Adequate margins for flutter and divergence are predicted from the use of existing, correlated stopped rotor and helicopter rotor analysis programs.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 208-223.

**100-KW HINGELESS METAL WIND TURBINE BLADE DESIGN, ANALYSIS, AND FABRICATION CONSIDERATIONS**

Donham, R. E.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 411-426.

**INHERENT UNCERTAINTIES IN METEOROLOGICAL PARAMETERS FOR WIND TURBINE DESIGN**

Doran, J. C.

Some of the uncertainties always associated with meteorological data and their causes are examined, examples are presented, and some implications for wind turbine design are suggested. Uncertainties discussed include the inability to duplicate experimental conditions from one day to the next, the stochastic nature of many of the meteorological variables of interest, and the fact that simple relationship derived in one location may be significantly altered by topographical or synoptic differences encountered at another.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 821-835.

**CONCEPTUAL DESIGN OF THE 7 MEGAWATT MOD-5B WIND TURBINE GENERATOR**

Douglas, R. R.

This paper describes the design of the next generation of wind turbine to the 2.5-MW Mod-2 HAWT, whose sole purpose is to provide electrical power for distribution by a major utility network. The cost-of-energy target for the Mod-5B is \$ 0.03 per kWh (1977), based on large quantity production. The development of the Mod-5B design from the Mod-2 configuration is described, including the rotor design, the generator system, refinement of miscellaneous components, size optimization, and cost of electricity.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111. pp. 61-78.

**THE BOEING MOD-2 WIND TURBINE SYSTEM RATED AT 2.5 MW**

Douglas, R. R.

A summary description of Mod-2 development and of the resulting system hardware is provided. The program has been structured to achieve commercial objectives by a substantial concept selection effort, comparatively few firm requirements imposed on the contractor, and encouragement of commercial practice application. Four significant changes from the Mod-0 and Mod-1 designs are discussed, which are the use of a soft shell type tower, an epicyclic gear box, a quill shaft to attenuate 2/rev torque and power oscillations, and a rotor designed primarily to commercial steel fabrication standards. (See paper by G. N. Davison at same conference.)

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 211-219.

**WIND ENERGY SYSTEM TIME-DOMAIN (WEST) ANALYZERS**

Dreier, M. E. , and Hoffman, J. A.

Using the latest hybrid electronics technology, a portable analyzer which simulates in real time the complex nonlinear dynamics of horizontal axis wind energy systems has been constructed. Math models for an aeroelastic rotor featuring nonlinear aerodynamic and inertial terms have been implemented with high speed digital controllers and analog calculation; this rotor model is then combined with other math models of elastic supports, control systems, a power train, and gimballed rotor kinematics. The analyzer also features a stroboscopic display system graphically depicting distributed blade loads, motion, and other aerodynamic functions on a cathode ray tube. Limited correlation efforts have shown good comparison between the results of this analyzer and other sophisticated digital simulations that have in turn been correlated with test data.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148,  
pp. 261-264.

**PLANS FOR WIND ENERGY SYSTEM SIMULATION**

Dreier, M. E.

Two new analysis tools, on a digital computer code and the other a special purpose hybrid computer, are introduced. The digital computer program, the Root Perturbation Method or RPM, is a new implementation of the classic Floquet procedure which circumvents numerical problems associated with the extraction of Floquet roots. The hybrid computer, the Wind Energy System Time-domain simulator (WEST), yields real-time loads and deformation information essential to design and system stability investigations.

ERDA/NSF/07378-75/1 AER 75-07378, 1976.

**EVALUATION OF THE POTENTIAL ENVIRONMENT EFFECTS OF WIND ENERGY SYSTEM DEVELOPMENT  
INTERIM FINAL REPORT**

Duffy, M. A. , Jefferis, J. G. , Rogers, S. E. , Sticksel, P. R. , and Tolle, D. A.

NASA-CR-168110 DOE/NASA/3303-4, 1982.

**DEVELOPMENT OF METHODOLOGY FOR HORIZONTAL AXIS WIND TURBINE DYNAMIC ANALYSIS --  
SUMMARY REPORT**

Dugundji, J.

NASA-CR-165385 DOE/NASA/3303-1, 1981.

**GENERAL REVIEW OF THE MOSTAS COMPUTER CODE FOR WIND TURBINES**

Dugundji, J. , and Wendell, J. H.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 165-172.

**REVIEW OF ANALYSIS METHODS FOR ROTATING SYSTEMS WITH PERIODIC COEFFICIENTS**

Dugundji, J. , and Wendell, J. H.

This paper reviews two of the more common procedures for analyzing the stability and forced response of equations with periodic coefficients, namely, (1) the use of Floquet methods and (2) the use of multiblade coordinate and harmonic balance methods. These procedures are compared with those of the more-familiar constant coefficient systems.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 53-60.

# **AEROELASTIC ANALYSIS OF WIND ENERGY CONVERSION SYSTEMS**

Dugundji, J.

An aeroelastic investigation of horizontal axis wind turbines is described. The study is divided into two simpler areas, namely, the aeroelastic stability of a single blade on a rigid tower, and the mechanical vibrations of the rotor system on a flexible tower. Some resulting instabilities and forced vibration behavior are described.

80N33357 NASA-TP-1729

# **WIND: COMPUTER PROGRAM FOR CALCULATION OF THREE DIMENSIONAL POTENTIAL COMPRESSIBLE FLOW ABOUT WIND TURBINE ROTOR BLADES**

Dulikravich, D. S.

A computer program is presented which numerically solves an exact, full potential equation (FPE) for three dimensional, steady, inviscid flow through an isolated wind turbine rotor. The program automatically generates a three dimensional, boundary conforming grid and solves the FPE by iteration while fully accounting for both the rotating cascade and Coriolis effects. The numerical techniques incorporated involve rotated, time-dependent finite-differencing, a finite volume method, artificial viscosity in conservative form, and a successive line over-relaxation combined with the sequential grid refinement procedure to accelerate the iterative convergence rate. Consequently, the WIND program is capable of accurately analyzing incompressible and compressible flows, including those that are locally transonic and terminated by weak shocks. The program can also be used to analyze the flow around isolated aircraft propellers and helicopter rotors in hover as long as the total relative Mach number of the oncoming flow is subsonic.

80A28804 and 80N18497 NASA-TM-81438 and AIAA Paper 80-0607; also Proceedings, Wind Energy Conference, 1980, American Institute of Aeronautics and Astronautics, pp. 14-19.

# **NUMERICAL CALCULATION OF STEADY INVISCID FULL POTENTIAL COMPRESSIBLE FLOW ABOUT WIND TURBINE BLADES**

Dulikravich, D. S.

The air flow through a propeller-type wind turbine rotor is characterized by three-dimensional rotating cascade effects about the inner portions of the rotor blades and compressibility effects about the tip regions of the blades. In the case of large rotor diameter and/or increased rotor angular speed, the existence of small supersonic zones terminated by weak shocks is possible. An exact nonlinear mathematical model (called a steady Full Potential Equation - FPE) that accounts for the above phenomena has been re-derived. An artificially time-dependent version of FPE was solved iteratively by a finite volume technique involving an artificial viscosity and a three-level consecutive mesh refinement. The exact boundary conditions were applied by generating a boundary conforming periodic computation mesh.

NASA-CR-165380 DOE/NASA/0029-1, 1981.

# **WIND FLOW CHARACTERISTICS IN THE WAKES OF LARGE WIND TURBINES: VOLUME I -- ANALYTICAL MODEL DEVELOPMENT**

Eberle, W. R.

79A10241 Proceedings, 13th Intersociety Energy Conversion Engineering Conference, Volume 3, 1978, Society of Automotive Engineers (Warrendale, Pennsylvania), pp. 2108-2114.

# **SIMWEST - A SIMULATION MODEL FOR WIND ENERGY STORAGE SYSTEMS**

Edsinger, R. W. , Warren, A. W. , Gordon, L. H. , and Chang, G. C.

This paper describes a comprehensive and efficient computer program for the modeling of wind energy systems with storage. The level of detail of SIMWEST (SIMulation Model for Wind Energy STORAGE) is consistent with evaluating the economic feasibility as well as the general performance of wind energy systems with energy storage options. The software package consists of two basic programs and a library of system, environmental, and control components. The first program is a pre-compiler which allows the library components to be put together in building block form. The second program performs the techno-economic system analysis with the required input/output, and the integration of system dynamics. An example of the application of the SIMWEST program to a current 100 kW wind energy storage system is given.

NASA-CR-165491 DOE/NASA/0129-1, 1982.

**DESIGN AND EVALUATION OF LOW-COST STAINLESS STEEL-FIBERGLASS-FOAM BLADES FOR LARGE WIND DRIVEN GENERATING SYSTEMS**

Eggert, W. S. Jr.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 267-285.

**DESIGN AND EVALUATION OF LOW COST BLADES FOR LARGE WIND DRIVEN GENERATING SYSTEMS**  
Eggert, W. S. Jr.

This paper describes the development of a low-cost blade concept based on spot-welded stainless steel spar and a non-structural airfoil shapes of foam and polyester fiberglass. Subjects discussed include the blade structural design, construction methods and materials, tooling concepts, technical and economic analyses, fatigue test program on materials and sub-structures, and a full-scale spar (20-ft long) for NASA fatigue testing.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 27-34.

**THE UTRC WIND ENERGY CONVERSION SYSTEM PERFORMANCE ANALYSIS FOR HORIZONTAL AXIS WIND TURBINES (WECSPER)**

Egolf, T. A. , and Landgrebe, A. J.

Major features of the WECSPER Code are (1) treatment of blades as lifting lines with a prescribed wake model; (2) solution for the wake-induced inflow and blade circulation using actual non-linear airfoil data; and (3) internal iteration to obtain compatible wake transport velocities and blade loadings. Also provided is an approximate treatment of wake distortions from tower shadow and wind shear. Selected applications to the analysis of existing wind turbines and correlation with limited test data are described.

NSF-RA-N-75-050, 1975, Mitre Corporation (Washington, DC), 536 pp.

**PROCEEDINGS, SECOND WORKSHOP ON WIND ENERGY CONVERSION SYSTEMS**

Eldridge, F. R. , Editor

ERDA and NSF/RANN, both planning to rapidly expand their programs on wind energy, decided in December 1974 to hold a second wind energy conversion systems workshop in June 1975 with the following purposes: To exchange information and new ideas on WECS; to help coordinate the rapidly growing ERDA and NSF WECS programs; to inform participants, as well as governmental, private and public sectors, of the plans and progress of the WECS programs; and to obtain inputs on WECS problem areas, needs, and requirements. During this three-day workshop, sixty-six technical presentations were given in sessions on design of large systems, mission and regional analyses, international activities in wind energy, technology development, energy storage, wind characteristics, institutional issues, agricultural and rural applications, and innovative and advanced system concepts. Eight working groups reported on the following areas of interest: Standards, testing, and nomenclature; possible utilization schedules; viability of large systems; wind characteristics/site survey; computer models/system design; possible improvements in conventional WECS; and interface with utilities and users. A list of attenders is included.

EPRI Report AP-3233-Vol. 3, 1984, Electric Power Research Institute (Palo Alto, California).

**EARLY UTILITY EXPERIENCE WITH WIND POWER GENERATION -- VOLUME 3: BONNEVILLE POWER ADMINISTRATION GOODNOE HILLS PROJECT**

Electric Power Research Institute

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 141-158.

**PUTTING WIND RESOURCE ATLASES TO USE**

Elliott, D. L.

This paper describes how the 12 recently-published wind energy resource atlases for the U.S. and its territories can be used to evaluate various aspects of an area's wind resource. Interpretation of atlas information is discussed. Techniques are described for extracting the magnitude of the wind resource, estimating seasonal and diurnal variations, determining certainty of estimates, and calculating the fraction of land area with a given wind resource.

NASA-CR-3778, 1984.

**NASA/MSFC GROUND-BASED DOPPLER LIDAR NOCTURNAL BOUNDARY LAYER EXPERIMENT (NOBLEX)**  
Emmitt, G. D.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers  
(New York), pp. 79-80.

**STATUS OF THE BOEING MOD-5B WIND TURBINE PROJECT**

Engle, W. W.

Major characteristics of this third-generation multi-megawatt HAWT, 320 feet in rotor diameter and rated at 3.2 MW, are described, along with a discussion of lessons learned from the 2.5-MW Mod-2 wind turbines from which its design is derived. Significant new features include a variable-speed constant-frequency generating system of the cycloconverter type. The prototype unit will be installed near Kahuku on the north shore of Oahu in the Hawaiian Islands.

**88N19014** NASA-TM-100274 DOE/NASA/20320-74

**TESTING OF A ONE-BLADED 30-METER-DIAMETER ROTOR ON THE DOE/NASA MOD-0 WIND TURBINE**

Ensworth, C. B. F. III, Corrigan, R. D., and Berkowitz, B. M.

Tests were conducted on the DOE/NASA Mod-O 200-kW horizontal-axis wind turbine in a one-bladed rotor configuration. The objectives of the test were to evaluate the performance, loads, and dynamic characteristics of a one-bladed rotor, and then to compare these parameters with those of an aerodynamically similar two-bladed rotor configuration. Test operations showed that this intermediate-size (15.2-m radius) one-bladed rotor configuration can be operated successfully. Test results show that the one-bladed rotor had cyclic blade loads comparable to those of a two-bladed rotor. A moderate power penalty equivalent to a reduction in wind speed of 1 m/sec occurred with the one-bladed rotor when operated at a rotor speed 50 percent higher than that of the two-bladed rotor.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers  
(New York), pp. 115-123.

**COMPARISON OF BLADE LOADS FOR AILERON AND TIP CONTROL ROTORS**

Ensworth, C. B. F. III

Blade load measurements were made during tests of the Mod-0 100 kW experimental HAWT for five different rotors with either aileron or partial span tip control surfaces. All configurations had downwind, 2-bladed rotors with teetered hubs. Comparisons were made with data for blade operating loads during power regulation tests and loss-of-load shutdown tests. The results indicate that the aileron rotors experience slightly higher cyclic flap bending moments during power generation. Blade loads during shutdown were comparable for both tip and aileron controlled rotors.

**86N10582** NASA-TM-87109 DOE/NASA/20320-66, 1985.

**IMPROVED STUD CONFIGURATIONS FOR ATTACHING LAMINATED WOOD WIND TURBINE BLADES**

Faddoul, J. R.

A series of bonded stud design configurations was screened on the basis of tension-tension cyclic tests to determine the structural capability of each configuration for joining a laminated wood structure (wind turbine blade) to a steel flange (wind turbine hub). Design parameters which affected the joint strength (ultimate and fatigue) were systematically varied and evaluated through appropriate testing. Two designs showing the most promise were used to fabricate additional test specimens to determine ultimate strength and fatigue curves. Test results for the bonded stud designs demonstrated that joint strengths approaching the 10,000 to 12,000 psi ultimate strength and 5000 psi high cycle fatigue strength of the wood epoxy composite could be achieved.

**84N10664** NASA-TM-83483 DOE/NASA/20320-53, 1983; also Proceedings, Wind Energy Expo '83 and National Conference, 1983, American Wind Energy Association (Washington, DC), pp. 317-357.

**EXAMINATION, EVALUATION AND REPAIR OF LAMINATED WOOD BLADES AFTER SERVICE ON THE MOD-0A WIND TURBINE**

Faddoul, J. R.

Laminated wood blades were designed, fabricated, and installed on a 200-KW wind turbine (Mod-0A). The machine uses a two-blade rotor with a diameter of 38.1 m (125 ft). Each blade weighs less than 1361 kg (3000 lb). After operating in the field, two blade sets were returned for inspection. One set had been in Hawaii for 17 months (7844 hr of operation) and the other had been at Block Island, Rhode Island, for 26 months (22 months operating - 7564 hr). The Hawaii set was returned because of one of the studs that holds the blade to the hub had failed. This was found to be caused by a combination

of improper installation and inadequate corrosion protection. No other problems were found. The broken stud (along with four others that were badly corroded) was replaced and the blades are now in storage. The Block Island set of blades was returned at the completion of the test program, but one blade was found to have developed a crack in the leading edge along the entire span. This crack was found to be the result of a manufacturing process problem but was not structurally critical. When a load-deflection test was conducted on the cracked blade, the response was identical to that measured before installation. In general, the laminate quality of both blade sets was excellent. No significant internal delamination or structural defects were found in any blade. The stud bonding process requires close tolerance control and adequate corrosion protection, but studs can be removed and replaced without major problems. Moisture content stabilization does not appear to be a problem, and laminated wood blades are satisfactory for long-term operation on Mod-0A wind turbines.

Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. III, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 113-143.

#### **AN OVERVIEW OF LARGE HORIZONTAL AXIS WIND TURBINE BLADES**

Faddoul, J. R.

Since the beginning of the DOE/NASA wind energy program, aluminum, steel, wood, and fiberglass/epoxy have been materials of construction for operational wind turbine blades. Polyurethane and cement have also been investigated at a preliminary level as potential low-cost materials for blades. This report presents a review of the experience that has been developed for all of these materials in blade lengths ranging from 60 to 150 feet. Fabrication processes are discussed for each blade material and cost and weight comparisons and/or projections are presented. Operational experience and problem areas are summarized.

83N19246 Proceedings, Large Horizontal-Axis Wind Turbine Conference, 1981, NASA CP-2230, DOE CONF-810752, pp. 303-328.

#### **STRUCTURAL FATIGUE TEST RESULTS FOR LARGE WIND TURBINE BLADE SECTIONS**

Faddoul, J. R. , and Sullivan, T. L.

In order to provide quantitative information on the operating life capabilities of wind turbine rotor blade concepts for root-end load transfer, a series of cantilever beam fatigue tests was conducted. Fatigue tests were conducted on a laminated wood blade with bonded steel studs, a low cost steel spar (utility pole) with a welded flange, a utility pole with additional root-end thickness provided by a swaged collar, fiberglass spars with both bonded and non-bonded fittings, and, finally, an aluminum blade with a bolted steel fitting (Lockheed Mod-0 blade). Photographs, data, and conclusions for each of these tests are presented. In addition, the aluminum blade test results are compared to field failure information; these results provide evidence that the cantilever beam type of fatigue test is a satisfactory method for obtaining qualitative data on blade life expectancy and for identifying structurally under-designed areas (hot spots).

NASA-TM-81719 DOE/NASA/20320-30, 1981.

#### **TEST EVALUATION OF A LAMINATED WOOD WIND TURBINE BLADE CONCEPT**

Faddoul, J. R.

NASA-TT-F-16,170, 1975, Technical Translation.

#### **WIND ENGINES AND WIND INSTALLATIONS**

Fateyev, Y. M.

PB-265 823 FEA/B-77/121, 1977, Federal Energy Administration (Washington, DC).

#### **WIND ENERGY CONVERSION SYSTEMS MANUFACTURING AND SALES ACTIVITY 1975 AND 1976** Federal Energy Administration

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 257-260.

#### **RESEARCH OF LOW COST WIND GENERATOR ROTORS**

Fertis, D. G. , and Ross, R. S.

This feasibility program determined that it would be possible to significantly reduce the cost of manufacturing wind generator rotors by making them of cast urethane. Goodyear developed several high-modulus urethanes which were structurally tested at the University of Akron. A section of rotor was also cast and tested showing the excellent aerodynamic surface which results. A design analysis indicates that a cost reduction of almost ten to one can be achieved with a small weight increase to achieve the same structural integrity as expected of current rotor systems.

78N19638 Proceedings, Wind Turbine Structural Dynamics Conference, NASA CP 2034, DOE CONF-771148, 1977, pp. 243-254.

#### **FIXED PITCH WIND TURBINES**

Fenn, D. B. , and Viterna, L. A.

Wind turbines designed for fixed pitch operation offer potential reductions in the cost of the machine by eliminating many costly components. It was shown that a rotor can be designed which produces the same energy annually as Mod-0 but which regulates its power automatically by progressively stalling the blades as wind speed increases. Effects of blade twist, taper, root cutout, and airfoil shape on performance are discussed. Unfortunately, fixed pitch rotors are not self-starting when the pitch is set to maximize energy production per year. Various starting techniques are discussed.

NASA-TM-75404, 1980.

#### **LARGE WIND ENERGY CONVERTER: GROWIAN 3 MW**

Feustel, J. D. , Körber, F. , and Helm, S.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 52-56.

#### **METHODOLOGY FOR FATIGUE ANALYSIS OF WIND TURBINES**

Finger, R. W.

This paper presents a description of the fatigue analysis methodology employed by the Boeing Aerospace Company during the design, fabrication, and testing of the Mod-2 (2.5-MW) and Mod-5B (3.2-MW) HAWTs. Modifications to the methodology are explained which were made as operating data provided a better understanding of the loads/fatigue environment, together with the impact of these modifications. Primary conclusions drawn from this study are that analytical predictions of mean loads are adequate; predictions of cyclic loads are best derived from empirical models of test data; relative phase/frequency relationship of individual load components are significant; and present fatigue analysis methodology is conservative (safe).

Proceedings, Fourth Biennial Conference and Workshop on Wind Energy Conversion Systems, 1979, DOE CONF-791097, JBF Scientific (Washington, DC), pp. 119-139 and pp. 561-567.

#### **SUMMARY OF APRIL 1979 WORKSHOP ON LARGE WIND TURBINE DESIGN CHARACTERISTICS AND RESEARCH AND DEVELOPMENT REQUIREMENTS**

Finnegan, P. M.

This workshop included both horizontal and vertical axis wind turbines and was conducted by the NASA Lewis Research Center with support from Sandia Laboratories. The program consisted primarily of detailed technical presentations on wind turbine R&D activities supported by DOE, with additional presentations by private and foreign organizations. (see 80N16453 S. Lieblein for complete Proceedings.)

HSER-10592, 1987, Hamilton Standard (East Hartford, Connecticut).

#### **FINAL REPORT WTS-4 WIND TURBINE MEDICINE BOW, WYOMING**

86N18776 NASA-TM-87166 DOE/NASA/20320-68, 1986; also Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 497-501.

#### **SUMMARY OF TOWER DESIGNS FOR LARGE HORIZONTAL AXIS WIND TURBINES**

Frederick, G. R. , and Savino, J. M.

Towers for large horizontal axis wind turbines, machines with a rotor axis height above 30 meters and rated at more than 500 kW, have varied in configuration, materials of construction, type of construction, height, and stiffness. For example, the U.S. large HAWTs have utilized steel truss type towers and free-standing steel cylindrical towers. In Europe, the trend has been to use only free-standing and guyed cylindrical towers, but both steel and reinforced concrete have been used as materials of construction. These variations in materials of construction and type of construction reflect different engineering approaches to the design of cost effective towers for large HAWTs. Tower designs are the NASA/DOE Mod-5B presently being fabricated. Design goals and requirements that influence tower configuration, height and materials are discussed. In particular, experiences with United States large wind turbine towers are elucidated. Finally, current trends in tower designs for large HAWTs are highlighted.

82N22649 NASA-TM-82804 DOE/NASA/20320-39, 1982.

**EFFECT OF ROTOR CONFIGURATION ON GUYED TOWER AND FOUNDATION DESIGNS AND ESTIMATED COSTS FOR INTERMEDIATE SIZE HORIZONTAL AXIS WIND TURBINES**

Frederick, G. R. , Winemiller, J. R. , and Savino, J. M.

Three designs of a guyed cylindrical tower and its foundation for an intermediate size horizontal axis wind turbine generator are discussed. The primary difference in the three designs is the configuration of the rotor. Two configurations are two-blade rotors with teetering hubs - one with full span pitchable blades, the other with fixed pitch blades. The third configuration is a three-bladed rotor with a rigid hub and fixed pitch blades. In all configurations the diameter of the rotor is 38 meters and the axis of rotation is 30.4 meters above grade, and the power output is 200 kW and 400 kW. For each configuration the design is based upon for the most severe loading condition either operating wind or hurricane conditions. The diameter of the tower is selected to be 1.5 meters (since it was determined that this would provide sufficient space for access ladders within the tower) with guy rods attached at 10.7 meters above grade. Completing a design requires selecting the required thicknesses of the various cylindrical segments, the number and diameter of the guy rods, the number and size of soil anchors, and the size of the central foundation. The lower natural frequencies of vibration are determined for each design to ensure that operation near resonance does not occur. Finally, a cost estimate is prepared for each design. A preliminary design and cost estimate of a cantilever tower (cylindrical and not guyed) and its foundation is also presented for each of the three configurations.

AIAA-79-0732, 1979, American Institute of Aeronautics and Astronautics.

**FORMULATION OF THE AEROELASTIC STABILITY AND RESPONSE PROBLEM OF COUPLED ROTOR/SUPPORT SYSTEM**

Friedmann, P. , and Warmbrodt, W.

UCLA-ENG-7881, 1978, University of California Los Angeles.

**AEROELASTIC RESPONSE AND STABILITY OF A COUPLED ROTOR/SUPPORT WITH APPLICATION TO LARGE HORIZONTAL AXIS WIND TURBINES**

Friedmann, P. , and Warmbrodt, W.

UCLA-ENG-7880, 1978, University of California Los Angeles.

**AEROELASTIC STABILITY AND RESPONSE OF HORIZONTAL AXIS WIND TURBINE BLADES**

Friedmann, P. , Kottapalli, S. B. R. , and Rosen, A.

Chapter 8 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

**CHARACTERISTICS OF THE WIND**

Frost, W. , and Aspliden, C.

The characteristics of both the steady and fluctuating components of the wind are dealt with, both as an energy source and as aerodynamic forcing functions on wind turbine rotors. U.S. and worldwide wind resources are reviewed, including major methods of assessing these resources. Standard methods of measuring and describing wind turbulence are discussed, supplemented by information on turbulence measured from a rotational frame of reference.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 155-161.

**TWO-DIMENSIONAL TURBULENCE MODELS**

Frost, W. , and Lin, M-C.

Two-dimensional turbulence models, presented in NASA TP 1359 (Engineering Handbook on the Atmospheric and Environmental Guidelines for Use in Wind Turbine Generator Development) are compared with experimental measurements made using an array of instrumented towers. Discussions of the spatial correlation coefficient, the two-point spectrum or cross spectrum, and the coherence function are given. These models in general agree reasonably well with the experimental results. Measurements of the integral length scale, however, do not correlate well with the prediction model recommended in NASA TP 1359.

NASA-TP-1359 and NASA-TP-1389 for Summary, 1978 and 1979.

**ENGINEERING HANDBOOK ON THE ATMOSPHERIC ENVIRONMENTAL GUIDELINES FOR USE IN WIND TURBINE GENERATOR DEVELOPMENT**

Frost, W. , Long, B. H. , and Turner, R. E.

This comprehensive handbook provides, in a working engineering format, the environmental design criteria necessary

for the development of reliable and productive wind turbine generators. More specifically, inputs are provided for structural and dynamic analyses in the form of wind loading (normal and extremes), turbulence levels, and snow and ice loading, although the general problem of siting wind turbines is not addressed directly. Chapters address wind speed; wind shear; turbulence; wind direction; ice and snow loadings, and auxiliary climatological factors such as precipitation and temperature. Each chapter starts with a summary of specific parameters recommended for the design of a wind turbine that might be sited generally in the U.S. A collection from the literature of the more-reliable data applicable to wind turbine design is presented with interpretation to make these data more directly useful. Extensive references are listed at the end of each chapter for further information.

NASA-CR-174794 DOE/NASA/0373, 1984.

**THERMAL-STRESS ANALYSIS FOR A WOOD COMPOSITE BLADE**  
Fu, K. C. , and Harb, A.

NASA-CR-159725 DOE/NASA/5906-79/1, 1979.

**EVALUATION OF FEASIBILITY OF PRESTRESSED CONCRETE FOR USE IN WIND TURBINE BLADES**  
Furlong, D. B. , Londahl, D. S. , Perry, D. J. , and Lieblein, S.

NASA-CR-179543 DOE/NASA/0006-3, 1986.

**DESIGN AND DYNAMIC SIMULATION OF A FIXED PITCH 56 kW WIND TURBINE DRIVE TRAIN WITH A CONTINUOUSLY VARIABLE TRANSMISSION**  
Gallo, C. , Pintz, A. , Kasuba, R. , and Spring, J. W.

COO/2578-1/1, -1/2, and -1/3, 1977, General Electric Company (King of Prussia, Pennsylvania)

**WIND ENERGY MISSION ANALYSIS**  
Garate, J. A.

Executive Summary, -1/1; Final Report, -1/2; and Final Report Appendices A - J, -1/3.

77N31614 NASA-TM-73745 ERDA/NASA-1028/77/3, 1977.

**INVESTIGATION OF EXCITATION CONTROL FOR WIND-TURBINE GENERATOR STABILITY**  
Gebben, V. D.

High speed horizontal axis wind turbine generators with blades on the downwind side of the support tower require special design considerations to handle disturbances introduced by the flow wake behind the tower. Experiments and analytical analyses were made to determine benefits that might be obtained by using the generator exciter to provide system damping for reducing power fluctuations.

NASA-CR-174734 DOE/NASA/0153-1, 1984.

**MOD-5A WIND TURBINE GENERATOR PROGRAM DESIGN REPORT -- VOLUME I: EXECUTIVE SUMMARY**  
General Electric Company (King of Prussia, Pennsylvania)

NASA-CR-159494 DOE/NASA/0058-79/1, 1979.

**MOD-1 WIND TURBINE GENERATOR FAILURE MODES AND EFFECTS ANALYSIS**  
General Electric Company (King of Prussia, Pennsylvania)

NASA-CR-159495 DOE/NASA/0058-79/2, 1979.

**MOD-1 WIND TURBINE GENERATOR ANALYSIS AND DESIGN REPORT**  
General Electric Company (King of Prussia, Pennsylvania)

NASA-CR-159497 DOE/NASA/0058-79/3, 1979.

**MOD-1 WIND TURBINE GENERATOR ANALYSIS AND DESIGN REPORT -- EXECUTIVE SUMMARY**  
General Electric Company (King of Prussia, Pennsylvania)

EPRI Report ER-978, 1979, Electric Power Research Institute (Palo Alto, California).

**REQUIREMENTS ASSESSMENT OF WIND POWER PLANTS IN ELECTRIC UTILITY SYSTEMS -- VOLUMES 1, 2, AND 3**  
General Electric Company (King of Prussia, Pennsylvania)

NASA-CR-134934 ERDA/NASA/19403-76/1, 1976.

**DESIGN STUDY OF WIND TURBINES 50-kW TO 3000-kW FOR ELECTRIC UTILITY APPLICATIONS --  
VOLUME I, SUMMARY REPORT**

General Electric Company (King of Prussia, Pennsylvania)

NASA-CR-134935 ERDA/NASA/19403-76/2, 1976.

**DESIGN STUDY OF WIND TURBINES 50-kW TO 3000-kW FOR ELECTRIC UTILITY APPLICATIONS --  
VOLUME II, ANALYSIS AND DESIGN**

General Electric Company (King of Prussia, Pennsylvania)

NASA-CR-135121 ERDA/NASA/19403-76/3, 1976.

**DESIGN STUDY OF WIND TURBINES 50-kW TO 3000-kW FOR ELECTRIC UTILITY APPLICATIONS --  
VOLUME III, SUPPLEMENTARY DESIGN AND ANALYSIS TASKS**

General Electric Company (King of Prussia, Pennsylvania)

Proceedings, National Conference, American Wind Energy Association, Summer 1980, AWEA (Washington, DC),  
pp. 46-48.

**LIGHTNING PROTECTION FOR COMPOSITE ROTOR BLADES**

Gewehr, H. W.

This paper discusses a recent test program aimed at developing an optimum lightning protection system for a large composite WECS rotor blade. Optimization provides not only adequate, low-cost protection from lightning strokes, but also preserves the inherently-low TV interference profile of composite blades by avoiding the use of large areas of metal. Tests are described which used long arc strokes on protected and unprotected blade specimens, up to 200,000 amps without damage to the protected specimens.

NASA-CR-159775, 1979.

**DESIGN, FABRICATION, TEST, AND EVALUATION OF A PROTOTYPE 150-FT-LONG COMPOSITE WIND  
TURBINE BLADE**

Gewehr, H. W.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111, pp. 309-324.

**LARGE, LOW COST COMPOSITE WIND TURBINE BLADES**

Gewehr, H. W.

Various studies have shown that the cost of energy decreases with increasing rotor size in wind turbine generator systems, and that the cost of the rotor is a major contributor to initial procurement and annual operating costs. In an effort to reduce rotor cost, NASA Lewis Research Center, with Department of Energy funding, initiated a program to develop a large, low-cost wind turbine blade representative of a design for a 300 ft-diameter wind generator system. This paper describes the design, analysis, and test results of that program and its extension to a follow-on program: Fabrication of two composite blades for the Mod-1 200-ft diameter wind turbine.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148,  
pp. 157-166.

**DRIVE TRAIN DYNAMIC ANALYSIS**

Giansante, N.

A method for performing parametric variations in drive train dynamic analysis is described which models the individual components of a drive system, forms the appropriate system interface coordinates, and calculates the system dynamic response at particular frequencies. Application of the method for prediction of the dynamic response characteristics of a helicopter transmission and a comparison of results with test data is included.

**80N16480** Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP  
2106, DOE CONF-7904111, pp. 375-384.

**SIMULATION STUDIES OF MULTIPLE LARGE WIND TURBINE GENERATORS ON A UTILITY NETWORK**

Gilbert, L. J. , Triezenberg, D. M.

The potential electrical problems that may be inherent in the inertia of clusters of wind turbine generators and an electric

utility network were investigated. Preliminary and limited results of an analog simulation of two Mod-2 wind generators tied to an infinite bus indicate little interaction between the generators and between the generators and the bus. The system demonstrated transient stability for the conditions considered.

**79A46547** Proceedings, Workshop on Economic and Operational Requirements and Status of Large Scale Wind Systems, 1979, Altas Corporation (Santa Cruz, California), pp. 388-402.

**LEWIS RESEARCH CENTER STUDIES OF MULTIPLE LARGE WIND TURBINE GENERATORS ON A UTILITY NETWORK**

Gilbert, L. J. , and Triezenberg, D. M.

A NASA-Lewis program to study the anticipated performance of a wind turbine generator farm on an electric utility network is surveyed. The paper describes the approach of the Lewis Wind Energy Project Office to developing analysis capabilities in the area of wind turbine generator-utility network computer simulations. Attention is given to areas such as, the Lewis Purdue hybrid simulation, an independent stability study, DOE multi-unit plant study, and the WEST simulator. Also covered are the Lewis mod-2 simulation including analog simulation of a two wind turbine system and comparison with Boeing simulation results, and gust response of a two machine model. Finally future work to be done is noted and it is concluded that the study shows little interaction between the generators and between the generators and the bus.

**78N26542** NASA-TM-78902; also Ph.D. Thesis, Toledo University (Ohio).

**TRANSIENT RESPONSE TO THREE-PHASE FAULTS ON A WIND TURBINE GENERATOR**

Gilbert, L. J.

In order to obtain a measure of its responses to short circuits a large horizontal axis wind turbine generator was modeled and its performance was simulated on a digital computer. Simulation of short circuit faults on the synchronous alternator of a wind turbine generator, without resort to the classical assumptions generally made for that analysis, indicates that maximum clearing times for the system tied to an infinite bus are longer than the typical clearing times for equivalent capacity conventional machines. Also, maximum clearing times are independent of tower shadow and wind shear. Variation of circuit conditions produce the modifications in the transient response predicted by analysis.

**78N17467** NASA-TM-73861 DOE/NASA/1028-77/10, 1977.

**SYNCHRONIZATION OF THE DOE/NASA 100-KILOWATT WIND TURBINE GENERATOR WITH A LARGE UTILITY NETWORK**

Gilbert, L. J.

The DOE/NASA 100 kilowatt wind turbine generator system was synchronized with a large utility network. The system equipments and procedures associated with the synchronization process were described. Time history traces of typical synchronizations were presented indicating that power and current transients resulting from the synchronizing procedure are limited to acceptable magnitudes.

NASA-TM-X-73613 ERDA/NASA-1028-77/12, 1977.

**SYNCHRONIZATION OF THE ERDA-NASA 100-kW WIND TURBINE GENERATOR WITH LARGE UTILITY NETWORKS**

Gilbert, L. J. , and Hwang, H. H.

NASA-TM-X-73459 ERDA/NASA/1028-77/8, 1976.

**TRANSIENT ANALYSIS OF UNBALANCED SHORT CIRCUITS OF THE ERDA-NASA 100-kW WIND TURBINE ALTERNATOR**

Gilbert, L. J. , and Hwang, H. H.

**76N18672** NASA-TM-X-71864, 1976.

**A 100-kW EXPERIMENTAL WIND TURBINE: SIMULATION OF STARTING, OVERSPEED, AND SHUTDOWN CHARACTERISTICS**

Gilbert, L. J.

The ERDA/NASA 100 kW experimental wind turbine is modeled on a digital computer in order to study the performance of a wind turbine under operating conditions. Simulation studies of starting, overspeed, and shutdown performance were made. From these studies operating procedures, precautions, and limitations are prescribed.

**83N29813** NASA-TM-83432 DOE/NASA/20320-46, 1983; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 783-794.

#### **RESULTS OF FREE YAW TESTS OF THE MOD-0 100 KILOWATT WIND TURBINE**

Glasgow, J. C. , and Corrigan, R. D.

Tests were conducted on the Mod-O 100 kW experimental wind turbine to provide data on yaw alignment characteristics of a large horizontal axis wind turbine with its yaw restraint removed (i.e. , in free yaw). The wind turbine consisted of a downwind horizontal axis rotor mounted on a tubular tower. Three rotor configurations were tested. Each rotor was teetered, coned 3 deg and tip-controlled. Two of the rotors had pitch-flap coupling or Delta-3, and one rotor had none. The two rotors with Delta-3 differed in the airfoil used in the tip sections. Test results indicate the rotor without pitch-flap coupling did not align closer than 25 deg with the wind, and pitch-flap coupling improved the wind turbine's alignment with the wind. Yaw damping was shown to have a favorable effect on free yaw characteristics. The change in the tip airfoil section was shown to affect the free yaw alignment also. The rotors with Delta-3 were shown to be capable of responding to wind shifts and exhibited stable operating properties.

**83N19234** Proceedings, Large Horizontal-Axis Wind Turbine Conference, 1981, NASA CP-2230, DOE CONF-810752, pp. 87-102.

#### **STALL INDUCED INSTABILITY OF A TEETERED ROTOR**

Glasgow, J. C. , and Corrigan, R. D.

Recent tests on the 38m Mod-0 horizontal experimental wind turbine yielded quantitative information on stall induced instability of a teetered rotor. Tests were conducted on rotor blades with NACA 230 series and NACA 64<sub>3</sub>-618 airfoils at low rotor speeds to produce high angles of attack at relatively low wind speeds and power levels. The behavior of the rotor shows good agreement with predicted rotor response based on blade angle of attack calculations and airfoil section properties. The untwisted blades with the 64 series airfoil sections had a slower rate of onset of rotor instability when compared with the twisted 230 series blades, but high teeter angles and teeter stop impacts were experienced with both rotors as wind speeds increased to produce high angles of attack on the outboard portion of the blade. The relative importance of blade twist and airfoil section stall characteristics on the rate of onset of rotor instability with increasing wind speed was not established however. Blade pitch was shown to be effective in eliminating rotor instability at the expense of some loss in rotor performance near rated wind speed.

**83N19232** Proceedings, Large Horizontal-Axis Wind Turbine Conference, 1981, NASA CP-2230, DOE CONF-810752, pp. 53-67.

#### **THE RESPONSE OF A 38M HORIZONTAL AXIS TEETERED ROTOR TO YAW**

Glasgow, J. C. , Pfanner, H. G. , and Westerkamp, E. J.

Recent tests on the 38m Mod-0 100 kW horizontal axis experimental wind turbine yielded quantitative data on the teeter response of a rotor to yaw. The test results indicate that yaw rates as high as 5 deg/s could be used in emergency situations to unload and slow a rotor for intermediate sized (500 Kw) wind turbines. The results also show that teeter response is sensitive to the direction of yaw, and that teeter response to yaw is reduced as either the rotor speed or the blade lock number is increased.

**83N14688** NASA-TM-82778 DOE/NASA/20320-35, 1980; also Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. II, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 307-321.

#### **THE EFFECT OF YAW ON HORIZONTAL AXIS WIND TURBINE LOADING AND PERFORMANCE**

Glasgow, J. C. , Corrigan, R. D. , and Miller, D. R.

The Mod-0 100 kW experimental wind turbine was tested to determine the effects of yaw on rotor power, blade loads and teeter response. The wind turbine was operated for extended periods at yaw angles up to 49 deg to define average or mean response to yaw. It was determined that the effect of yaw on rotor power can be approximated by the cube of the velocity normal to the rotor disc as long as the yaw angle is less than 30 deg. Blade bending loads were relatively unaffected by yaw, but teeter angle increased with wind speed as the magnitude of the yaw angle exceeded 30 deg indicating a potential for teeter stop impacts at large yaw angles. No other adverse effects due to yaw were noted during the tests.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 53-67.

#### **THE RESPONSE OF A 38m HORIZONTAL AXIS TEETERED ROTOR TO YAW**

Glasgow, J. C. , Pfanner, H. G. , and Westerkamp, E. J.

Results are presented of recent tests on the Mod-0 100 kW HAWT which yielded quantitative data on the response of a rotor to yaw. Indications are that yaw rates as high as 5 deg/s could be used in emergency situations to unload and slow a rotor of an intermediate-sized (500 kW) wind turbine. Teeter response was found to be sensitive to the direction of yaw and is reduced as either the rotor speed or the blade Lock Number is increased.

**82N23710 and 81N22472** NASA-TM-81744 DOE/NASA/1028-31, 1981; also Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 225-234.

**COMPARISON OF UPWIND AND DOWNWIND ROTOR OPERATIONS OF THE DOE/NASA 100-KW MOD-0 WIND TURBINE**

Glasgow, J. C. , Miller, D. R. , and Corrigan, R. D.

Tests were conducted on a 38m diameter horizontal axis wind turbine, which had first a rotor downwind of the supporting truss tower and then upwind of the tower. Aside from the placement of the rotor and the direction of rotation of the drive train, the wind turbine was identical for both tests. Three aspects of the test results are compared: rotor blade bending loads, rotor teeter response, and nacelle yaw moments. As a result of the tests, it is shown that while mean flatwise bending moments were unaffected by the placement of the rotor, cyclic flatwise bending tended to increase with wind speed for the downwind rotor while remaining somewhat uniform with wind speed for the upwind rotor, reflecting the effects of increased flow disturbance for downwind rotor. Rotor teeter response was not significantly affected by the rotor location relative to the tower, but appears to reflect reduced teeter stability near rated wind speed for both configurations. Teeter stability appears to return above rated wind speed, however. Nacelle yaw moments are higher for the upwind rotor but do not indicate significant design problems for either configuration.

**80A28836 and 80N19613** NASA-TM-81445 DOE/NASA/1028-80/26 AIAA Paper A80-28801, 1979; also Proceedings, Wind Energy Conference, 1980, American Institute of Aeronautics and Astronautics, pp. 261-268.

**TEETERED, TIP-CONTROLLED ROTOR - PRELIMINARY TEST RESULTS FROM MOD-0 100-KW EXPERIMENTAL WIND TURBINE**

Glasgow, J. C. , and Miller, D. R.

A series of tests is currently being conducted using the DOE/NASA 100 kW Experimental Wind Turbine with a two-bladed, teetered rotor with 30% span tip control. Preliminary evaluation test results indicates that the teetered rotor significantly decreases loads on the yaw drive mechanism and reduces blade cyclic flapwise bending moments by 25% at the 20% span location when compared to rigid hub rotor. The teetered hub performed well but did impact the teeter stops on occasion as wind speed and/or direction varied rapidly. The tip-controlled rotor performed satisfactorily with some expected reduction in control authority when compared to the full span pitchable blade. Discrepancies between predicted and measured aerodynamic performance indicate that a review of techniques used to calculate rotor power is in order.

**79A46537** Proceedings, Workshop on Economic and Operational Requirements and Status of Large Scale Wind Systems, 1979, Altas Corporation (Santa Cruz, California), pp. 215-247.

**UTILITY OPERATIONAL EXPERIENCE ON THE NASA/DOE MOD-0A 200 KW WIND TURBINE**

Glasgow, J. C. , and Robbins, W. H.

The Mod-0A 200 kW Wind Turbine was designed and fabricated by the Lewis Research Center of the NASA under the direction of the U.S. Department of Energy. The project is a part of the Federal Wind Energy Program and is designed to obtain early wind turbine operation and performance data while gaining initial experience in the operation of large, horizontal axis wind turbines in typical utility environments. On March 6, 1978, the Mod-0A wind turbine was turned over to the Town of Clayton Light and Water Plant, Clayton, NM, for utility operation and on December 31, 1978 the machine had completed ten months of utility operation. This paper describes the machine and documents the recent operational experience at Clayton, NM.

**79N20494** NASA-TM-79084 DOE/NASA/1004-79/1, 1979; Proceedings, 6th Energy Technology Conference, 1979, American Gas Association, Gas Research Institute, Electric Power Research Institute, and Thomas Alva Edison Foundation (Washington, DC).

**UTILITY OPERATIONAL EXPERIENCE ON THE NASA/DOE MOD-0A 200-KW WIND TURBINE**

Glasgow, J. C. , and Robbins, W. H.

The Mod-0A 200 wind turbine was designed and fabricated as part of the Federal Wind Energy Program. Early wind turbine operation and performance data were obtained while gaining initial experience in the operation of large, horizontal axis wind turbines in typical utility environments. The Mod-0A wind turbine was turned over to the Town of Clayton Light and Water Plant, Clayton, NM, for utility operation and on December 31, 1978, the machine had completed ten months of

utility operation. The machine is described and the recent operational experience at Clayton, New Mexico, is documented.

**79A10234 and 78N26552** NASA-TM-78915 DOE/NASA/1028-78/18, 1978; also Proceedings, 13th Intersociety Energy Conversion Engineering Conference, Volume 3, 1978, Society of Automotive Engineers (Warrendale, Pennsylvania), pp. 2052-2059.

**DESIGN AND OPERATING EXPERIENCE ON THE U.S. DEPARTMENT OF ENERGY EXPERIMENTAL MOD-0 100 KW WIND TURBINE**

Glasgow, J. C. , and Birchenough, A. G.

The Mod-0 100 kW Experimental Wind Turbine was designed and fabricated by NASA, as part of the Federal Wind Energy Program, to assess technology requirements and engineering problems of large wind turbines. The machine became operational in October 1975 and has demonstrated successful operation in all of its design modes. During the course of its operations the machine has generated a wealth of experimental data and has served as a prototype developmental test bed for the Mod-0A operational wind turbines which are currently used on utility networks. This paper describes the mechanical and control systems as they evolved in operational tests and describes some of the experience with various systems in the downwind rotor configuration.

**78N19628** Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp.117-150.

**DOE/NASA MOD-0 100KW WIND TURBINE TEST RESULTS**

Glasgow, J. C.

The Wind Turbine demonstrates the capability of automatic unattended operation, including startup, achieving synchronism, and shutdown as dictated by wind conditions. During the course of these operations, a wealth of engineering data was generated. Some of the data which is associated with rotor and machine dynamics problems encountered, and the machine modifications incorporated as a solution are presented. These include high blade loads due to tower shadow, excessive nacelle yawing motion, and power oscillations. The results of efforts to correlate measured wind velocity with power output and wind turbine loads are also discussed.

**77N10640** NASA-TM-X-71601 DOE/NASA/1028-77/5, 1976.

**EARLY OPERATION EXPERIENCE ON THE ERDA/NASA 100 KW WIND TURBINE -- ROTOR BLADE LOADS**

Glasgow, J. C. , and Linscott, B. S.

As part of the Energy Research and Development Administration (ERDA) wind energy program, NASA Lewis Research Center is testing an experimental 100-kW wind turbine. Rotor blade and drive shaft loads and tower deflection were measured during operation of the wind turbine at rated rpm. The blade loads measured are higher than anticipated. Preliminary results indicate that air flow blockage by the tower structure probably caused the high rotor blade bending moments.

**79A21302 and 79N12548** NASA-TM-79021 DOE/NASA/1028-78/20; also Proceedings, Conference on Industrial Applications of Microprocessors, 1978, Institute of Electrical and Electronics Engineers, 15 p.

**MICROPROCESSOR CONTROL OF A WIND TURBINE GENERATOR**

Gnecco, A. J. , and Whitehead, G. T.

This paper describes a microprocessor based system used to control the unattended operation of a wind turbine generator. The turbine and its microcomputer system are fully described with special emphasis on the wide variety of tasks performed by the microprocessor for the safe and efficient operation of the turbine. The flexibility, cost and reliability of the microprocessor were major factors in its selection.

**78N19632** Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp.179-186.

**METHODS OF ATTENUATING WIND TURBINE AC GENERATOR OUTPUT VARIATIONS**

Gold, H.

Wind speed variation, tower blockage and structural and inertial factors produce unsteady torque in wind turbines. Methods for modifying the turbine torque so that steady torque is delivered to the coupled AC generator are discussed. The method that may evolve will be influenced by the power use that develops and the trade-offs of cost, weight and complexity.

**86N18775** NASA-TM-87233 DOE/NASA/20320-69, 1985.

**MOD-2 WIND TURBINE FIELD OPERATIONS EXPERIMENT**

Gordon, L. H.

The three-machine, 7.5 MW Goodnoe Hills located near Goldendale, Washington and is now in a research/experimental operations phase that offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid; and the environment. Following a brief description of the turbine and project history, this paper addresses major problem areas and research and development test results. Field operations, both routine and non-routine, are discussed. Routine operation to date has produced over 13,379,000 KWh of electrical energy during 11,064 hr of rotation. Non-routine operation includes suspended activities caused by a crack in the low speed shaft that necessitated a redesign and reinstallation of this assembly on all three turbines. With the world's largest cluster back in full operation, two of the turbines will be operated over the next years to determine their value as energy producer. The third unit will be used primarily for conducting research tests requiring configuration changes to better understand the wind turbine technology. Technical areas summarized pertain to system performance and enhancements. Specific research tests relating to acoustics, TV interference, and wake effects conclude the paper.

**85A45512** Proceedings, 19th Intersociety Energy Conversion Engineering Conference, Volume 4, 1984, American Nuclear Society (La Grange Park, Illinois), pp. 2363-2368.

#### **MOD-2 WIND TURBINE FIELD OPERATIONS EXPERIENCE**

Gordon, L. H.

The Mod-2 wind turbine is now in a 2-year research/experimental operations phase which offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment. This paper addresses the field operations and research testing experienced at the Mod-2 Cluster Goodnoe Hills Research Test Site near Goldendale, WA. Field operation, both routine and non-routine, are discussed as well as the role of the participating utility. Technical areas discussed pertain to system performance and loads. Specific research tests relating to acoustics, TV interference, and wake effects are also discussed.

**84N13670** NASA-TM-83460 DOE/NASA/20305-9, 1983; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 133-144.

#### **MOD-2 WIND TURBINE DEVELOPMENT**

Gordon, L. H. , Andrews, J. S. , and Zimmerman, D. K.

The development of the Mod-2 turbine, designed to achieve a cost of electricity for the 100th production unit that will be competitive with conventional electric power generation is discussed. The Mod-2 wind turbine system (WTS) background, project flow, and a chronology of events and problem areas leading to Mod-2 acceptance are addressed. The role of the participating utility during site preparation, turbine erection and testing, remote operation, and routine operation and maintenance activity is reviewed. The technical areas discussed pertain to system performance, loads, and controls. Research and technical development of multimegawatt turbines is summarized.

**83N19262** Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 653-673.

#### **MOD-2 WIND TURBINE PROJECT ASSESSMENT AND CLUSTER TEST PLANS**

Gordon, L. H.

An assessment of the Mod-2 Wind Turbine project is presented based on initial goals and present results. Specifically, the Mod-2 background, project flow, and a chronology of events/results leading to Mod-2 acceptance is presented. After checkout/acceptance of the three operating turbines, NASA/LeRC will continue management of a two year test program performed at the DOE Goodnoe Hills test site. This test program is expected to yield data necessary for the continued development and optimization of wind energy systems. These test activities, their implementation, and the results to date are also presented.

**82N26807** NASA-TM-82906 DOE/NASA/20305-8, 1982

#### **MOD-2 WIND TURBINE SYSTEM CLUSTER RESEARCH TEST PROGRAM -- VOLUME 1: INITIAL PLAN**

Gordon, L. H.

Upon completion of the design and development of three Mod-2 wind turbines, a series of research experiments are planned to gather data on and evaluate the performance, environmental effects, and operation of a cluster as well as a single, large multimegawatt wind turbine. Information on the program objectives, a Mod-2 system description, a planned schedule, organizational roles, and responsibilities, is included.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 293-308.

#### **THE USE OF WOOD FOR WIND TURBINE BLADE CONSTRUCTION**

Gougeon, M. and Zuteck, M.

Topics discussed include historical problems with wood, a modern solution to these problems, the wood-resin composite, structural and economic considerations, quality control, wood as an engineering material, the feasibility of wooden wind turbine blades, and the cost of wood. Six photographs of the blade manufacturing process are included.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 355-362.

#### **MEASURED AND CALCULATED CHARACTERISTICS OF WIND TURBINE NOISE**

Greene, G. C.

Results are presented of an analytical and experimental investigation of wind turbine noise, which indicate that for configurations with the rotor downwind of the support tower the primary noise source is the rapid change in rotor loading occurring as a blade passes through the tower wake. Noise measurements are presented for solid and truss-type tower models with both upwind and downwind rotors, and upwind rotors are shown to be significantly quieter. Noise calculations based on averaged tower wake characteristics may not accurately represent the impulsive noise from downwind rotors.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 53-66.

#### **COMPARATIVE WIND TUNNEL TESTS AT HIGH REYNOLDS NUMBERS OF NACA 64-621 AIRFOILS WITH TWO AILERON CONFIGURATIONS**

Gregorek, G. M.

The 6" x 22" pressurized, blowdown wind tunnel at the OSU Aeronautical and Astronautical Research Laboratory was used to measure the surface pressures and wake momentum deficits on two-dimensional airfoil models of NACA 64-621 profile. Results presented in this paper include basic airfoil aerodynamic characteristics (without aileron deployment), aileron control effectiveness, aileron hinge moments, and chordwise force coefficients. The latter show unexpected positive (*i.e.*, power-producing) values in the post-stall region for large displacements of the aileron.

88N21593 NASA-TM-100802 DOE/NASA/20320-75

#### **COMPARISON OF PRESSURE DISTRIBUTIONS ON MODEL AND FULL-SCALE NACA 64-621 AIRFOILS WITH AILERONS FOR WIND TURBINE APPLICATION**

Gregorek, G. M. , Kuniega, R. J. , and Nyland, T. W.

The aerodynamic similarity between a small (4-inch chord) wind tunnel model and a full-scale wind turbine blade (24-foot tip section with a 36-inch chord) was evaluated by comparing selected pressure distributions around the geometrically similar cross sections. The airfoils were NACA 64-621 sections, including trailing-edge ailerons with a width equal to 38 percent of the airfoil chord. The model airfoil was tested in the OSU 6- by 12-inch High Reynolds Number Wind Tunnel; the full-scale blade section was tested in the NASA Langley Research Center 30- by 60-foot Subsonic Wind Tunnel. The model airfoil contained 61 pressure taps connected by embedded tubes to pressure transducers. A belt containing 29 pressure taps was fixed to the full-scale section at midspan to obtain surface pressure data. Lift coefficients were obtained by integrating pressures, and corrections were made for the 3-D effects of blade twist and downwash in the blade tip section. The results of the two different experimental methods correlated well for angles of attack from minus 4 to 36 degrees and aileron reflections from 0 to 90 degrees.

NASA-CR-180803 DOE/NASA/0330-2, 1987.

#### **WIND TUNNEL EVALUATION OF A TRUNCATED NACA 64-621 AIRFOIL FOR WIND TURBINE APPLICATIONS**

Gregorek, G. M. , and Law, S. P.

NASA-CR-135389 DOE/NASA/9773-78/1, 1977.

#### **DESIGN, FABRICATION, AND TEST OF A COMPOSITE MATERIAL WIND TURBINE ROTOR BLADE**

Griffiee, D. G. Jr. , Gustafson, R. E. , and More, E. R.

HSER 7293, 1977, Hamilton Standard (East Hartford, Connecticut).

**MOD-0 WIND TURBINE COMPOSITE MATERIAL MANUFACTURING PROTOTYPE BLADE -- INSPECTION AND TESTING**

Griffie, D. G. Jr. , More, E. R. , and Pinter, W. H.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 211-220.

**MEASUREMENT AND PREDICTION OF BROADBAND NOISE FROM LARGE HORIZONTAL AXIS WIND TURBINE GENERATORS**

Grosveld, F. W. , Shepherd, K. P. , and Hubbard, H. H.

A method is presented for predicting the broadband noise spectra of HAWTs, which includes contributions from such noise sources as the inflow turbulence to the rotor, the interactions between the turbulent boundary layers on the blade surfaces with their trailing edges, and the wake from a blunt trailing edge. The method is partly empirical and is based on acoustic measurements near large wind turbines and of airfoil models. Spectra are predicted for several HAWTs, and good agreement is found between predicted and measured far-field noise spectra for the Mod-2, WTS-4, Mod-0A, and U.S. Windpower HAWTs.

AIAA Journal, Propulsion and Power, Volume No. 4, 1985.

**PREDICTION OF BROADBAND NOISE FROM HORIZONTAL AXIS WIND TURBINES**

Grosveld, F. W.

Proceedings, Internoise '82 Conference, 1982, pp. 323-326.

**RADIATION OF AERODYNAMIC SOUND FROM LARGE WIND TURBINE GENERATORS**

Grosveld, F. W. , Shepherd, K. P. , and Hubbard, H. H.

NASA-CR-135344 DOE/NASA/3132-78/1, 1978.

**EMPLOYING STATIC EXCITATION CONTROL AND TIE-LINE REACTANCE TO STABILIZE WIND TURBINE GENERATORS**

Guo, T. , Hwang, H. H. , and Mozeico, H. V.

NASA-CR-179514 DOE/NASA/0367-1, 1986.

**DEVELOPMENT AND TESTING OF VORTEX GENERATORS**

Gyatt, G. W.

NASA-CR-174991 DOE/NASA/0341-1, 1985.

**DEVELOPMENT AND TESTING OF TIP DEVICES FOR HORIZONTAL AXIS WIND TURBINES**

Gyatt, G. W. , and Lissaman, P. B. S.

**82A24240** Proceedings, 12th International Symposium on Non-Mechanical Electrical Power Sources, 1980, Academic Press (London), pp. 227-243.

**REDOX STORAGE SYSTEMS FOR SOLAR APPLICATIONS**

Hagedorn, N. H. , and Thaller, L. H.

It is noted that the worldwide development of solar photovoltaic and wind turbine systems to meet a range of terrestrial electrical energy requirements has underscored the need for inexpensive and reliable electrical energy storage. The NASA Redox Energy Storage System, based on soluble aqueous iron and chromium chloride redox couples, has exhibited many system-related features which for the most part are unique to this storage system. The technology advances required in the two elements (electrodes and membranes), which are the key to its technological feasibility, have been attained and system development has begun. The design, construction, and testing of a 1-kW system integrated with a solar photovoltaic array is underway to provide early demonstration of the attractive system-related features of the NASA Redox Storage System. Also demonstrated will be its versatility and compatibility with a terrestrial solar photovoltaic electric power system.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 199-200.

**FLUTTER OF DARRIEUS WIND TURBINE BLADES: CORRELATION OF THEORY AND EXPERIMENT**  
Ham, N. D.

Acquisition of frequency data for the Alcoa 17-m LC and 1238229 wind turbines has permitted some limited correlation of the flutter analysis with experimental data, and this is briefly described here.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 77-93.

#### **FLUTTER OF DARRIEUS WIND TURBINE BLADES**

Ham, N. D.

The testing of Darrieus wind turbines has indicated that under certain conditions, serious vibrations of the blades can occur, involving flatwise bending, torsion, and chordwise bending. It is the purpose of this paper to develop a theoretical method of predicting the aeroelastic stability of the coupled bending and torsional motion of such blades with a view to determining the cause of these vibrations and a means of suppressing them.

HSER-9836, 1985, Hamilton Standard (East Hartford, Connecticut).

#### **CONTROL DYNAMICS TESTING OF THE WTS-4**

Hamilton Standard

HSER-9577, 1985, Hamilton Standard (East Hartford, Connecticut).

#### **VARIABLE FREQUENCY MODAL RESPONSE TESTING OF THE WTS-4**

Hamilton Standard

DOE/NASA/0530-1, 1985.

#### **AC MOTOR AND GENERATOR REQUIREMENTS FOR ISOLATED WECS**

Hanson, B. , McCleer, P. J. , Weinberg, B. , Park, G. L. , and Krauss, O.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 397-402.

#### **COST OF ENERGY EVALUATION**

Hasbrouck, T. M.

Cost of energy is based on three elements: Capital cost, operations and maintenance cost, and energy capture. Cost calculations for the planned WTS-3 3-MW HAWT are used as an example of the methodology. An artist's conception and preliminary specifications, characteristics, and performance of this advanced wind turbine are presented.

Proceedings, Windpower '87 Conference, 1987, American Wind Energy Association (Washington, DC), SERI/CP-217-3315, National Renewable Energy Laboratory (Golden, Colorado), pp. 7-13.

#### **PRELIMINARY RESULTS FROM THE DYNAMIC RESPONSE TESTING OF THE WESTINGHOUSE 600-kW WIND TURBINE**

Hausfeld, T. E. , Hock, S. M. , and Thresher, R. W.

This paper provides a first look at test data from this 43.3-meter diameter commercial HAWT, located at the Kahuku wind power station on Oahu in the Hawaiian Islands. Wind data were collected from five levels of anemometers on a tower upwind of the turbine. Three sets of 10-minute time histories are presented that cover power output, blade pitch angle, blade loads, and wind speeds. Tentative conclusions are that power output appears to be somewhat higher than predicted, the teetering hub is operating as expected, and a large part of the variance in blade flap moments is caused by low-frequency turbulence in the wind.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 130-134.

#### **USE OF HYDROGEN AND HYDROGEN-RICH COMPONENTS AS A MEANS OF STORING AND TRANSPORTING ENERGY**

Hausz, W.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 197-203.

#### **A PROPOSED NATIONAL WIND POWER R&D PROGRAM**

Heronemus, W.

NASA-CR-175056 DOE/NASA/4105-3, 1986.

#### **STATUS REPORT ON UTILITY INTERCONNECTION ISSUES FOR WIND POWER GENERATION**

Herrera, J. I. , Reddoch, T. W. , Sullivan, R. L. , and Lawler, J. S.

NASA-CR-174950 DOE/NASA/4105-1, 1985.

**EXPERIMENTAL INVESTIGATION OF A VARIABLE SPEED CONSTANT FREQUENCY ELECTRIC GENERATING SYSTEM FROM A UTILITY PERSPECTIVE**

Herrera, J. I. , Reddoch, T. W. , and Lawler, J. S.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 53-61.

**WIND POWER RESEARCH AT OREGON STATE UNIVERSITY**

Hewson, E. W.

PNL-4535 Report, 1983, Pacific Northwest Laboratories.

**FLOW VISUALIZATION STUDY OF THE MOD-2 WIND TURBINE WAKE**

Hiester, T. R. , Sronsky, R. A. , Waite, J. W. , Liu, H. T. , and Tacheron, P. H.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 195-212.

**WIND TURBINE SITING: A SUMMARY OF THE STATE OF THE ART**

Hiester, T. R.

This paper describes an efficient siting strategy founded on broad-based application of several techniques determined by local topography and meteorology. Topics include existing and supplementary wind data analysis; topographical indicators; biological indicators; geomorphological indicators; social and cultural indicators; numerical modeling; physical modeling; and the application of siting techniques.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 117-120.

**STATUS OF BUREAU OF RECLAMATION'S TWO SVU WIND TURBINES AT MEDICINE BOW, WYOMING**

Hightower, S. J.

This paper gives the status of the studies and operational testing being accomplished on a Hamilton Standard WTS-4 HAWT rated at 4 MW and on a Boeing Mod-2 HAWT rated at 2.5 MW. These two turbines, designated as System Verification Units, were constructed in parallel with a detailed feasibility study for a proposed 100 MW wind power project, the cost of which would be paid back with interest by marketing power at reasonable rates.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 153-156.

**ANALYSIS METHODS FOR WIND TURBINE CONTROL AND ELECTRICAL SYSTEM DYNAMICS**

Hinrichsen, E. N.

The hierarchical control structure of utility electric power systems is discussed, which has a well-established order of prime mover, generator, and system control functions. An analysis of wind turbine controls is discussed which considers the constraints imposed by the control structure of the receiving utility, so that conflicts between process and system control requirements are exposed and resolved.

DOE/NASA/0252-1, 1983.

**CONTROL OF LARGE WIND TURBINE GENERATORS CONNECTED TO UTILITY NETWORKS**

Hinrichsen, E. N.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 315-323.

**DYNAMICS AND STABILITY OF WIND TURBINE GENERATORS**

Hinrichsen, E. N. , and Nolan, P. J.

This paper describes the dynamic and stability properties of wind turbine generators connected to power distribution systems. Both synchronous and induction generators are considered. Wind turbines exhibit unusual phenomena compared steam and hydro units. General control requirements are discussed, as well as schemes for torsional damping, such as speed-sensitive stabilizers and blade pitch controls. Interaction between adjacent wind turbines in a cluster is also considered.

**80N33862** NASA-CR-165156 DOE/NASA/0134-1, 1980.

**MOD-2 WIND TURBINE FARM STABILITY STUDY**

Hinrichsen, E. N. , and Nolan, P. J.

The dynamics of single and multiple 2.5-MW, Boeing Mod-2 wind turbine generators (WTGs) connected to utility power systems were investigated. The analysis was based on digital simulation. Both time response and frequency response methods were used. The dynamics of this type of WTG are characterized by two torsional modes, a low-frequency "shaft" mode below 1 Hz and an "electrical" mode at 3-5 Hz. High turbine inertia and low torsional stiffness between turbine and generator are inherent features. Turbine control is based on electrical power, not turbine speed as in conventional utility turbine generators. Multi-machine dynamics differ very little from single machine dynamics.

**81A22526 and 81N12446** NASA-TM-81623; also Ph.D. Thesis (Delaware University) and Proceedings, Third Miami International Conference on Alternative Energy Sources, 1980, 35 pp.

#### **STABILITY OF LARGE HORIZONTAL-AXIS AXISYMMETRIC WIND TURBINES**

Hirschbein, M. S. , and Young, M. I.

The stability of large horizontal-axis, axisymmetric, power producing wind turbines is examined within the framework of an analytical model which includes dynamic coupling of the rotor, tower, and power generating system. The aerodynamic loading is derived from blade element theory. Each rotor blade was permitted two principal elastic bending degrees of freedom, one degree of freedom in torsion and controlled pitch as a rigid body. The rotor hub was mounted in a rigid nacelle which may yaw freely or in a controlled manner. The tower can bend in two principal directions and may twist. Also, the rotor speed can vary and may induce perturbation reactions within the power generating equipment. Stability is determined by the eigenvalues of a set of linearized constant-coefficient differential equations. All results presented are based on a 3-bladed, 300-ft diameter, 2.5-MW wind turbine. It is shown that unstable or weakly stable behavior can be caused by aerodynamic forces due to motion of the rotor blades and tower in the plane of rotation or by mechanical coupling between the rotor system and the tower.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 79-88.

#### **DESIGN OF A REAL-TIME WIND TURBINE SIMULATOR USING A CUSTOM PARALLEL ARCHITECTURE**

Hoffman, J. A. , Gluck, R. , and Sridhar, S.

The design of a new simulator, the WEST-3 computer, is described which has been developed specifically for the dynamic analysis of wind energy systems in real time. Many computations are performed in parallel by pure digital processors, each of which can be programmed individually for increased flexibility and generality. Design features are described to show how the system produces high-speed solutions of nonlinear time-domain equations. Computational units are interfaced to each other and to other portions of the simulation using special serial buses, which can be patched together in essentially any configuration to balance the input/output requirements and achieve through-put rates much higher than those of a rigid bus architecture.

NASA-CR-174983 DOE/NASA/0247-3, 1985.

#### **WEST-3 WIND TURBINE SIMULATOR DEVELOPMENT -- VOLUME 3: SOFTWARE**

Hoffman, J. A. , and Sridhar, S.

NASA-CR-159737 DOE/NASA/0026-79/1, 1979.

#### **WIND ENERGY SYSTEM TIME-DOMAIN (WEST) ANALYZERS USING HYBRID SIMULATION TECHNIQUES**

Hoffman, J. A.

NASA-CR-135152 DOE/NASA/9767-77/1, 1977.

#### **COUPLED DYNAMICS ANALYSIS OF WIND ENERGY SYSTEMS**

Hoffman, J. A.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 277-286.

#### **DYNAMICS OF AN EXPERIMENTAL TWO BLADED HORIZONTAL AXIS WIND TURBINE WITH BLADE CYCLIC PITCH VARIATION**

Hohenemser, K. H. , and Swift, A. H. P.

Structural dynamic and yaw dynamic test results are summarized for a HAWT which incorporates the combination of two features: The application of blade cyclic pitch variation and the use of yaw angle control for rotor speed and torque regulation. Because of passive cyclic pitch variation, the rotor can be rapidly yawed without encountering gyroscopic and aerodynamic hub moments and without noticeable out-of-plane blade excursions. The two-bladed, 7.6-m diameter, upwind rotor is vane stabilized and of very simple and rugged design. The rotor-to-tail vane furl angle was controlled through an electric actuator by a manually-operated toggle switch overridden by an automatic rotor overspeed relay.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 195-218.

**SOME ALTERNATIVE DYNAMIC DESIGN CONFIGURATIONS FOR LARGE HORIZONTAL AXIS WECS**  
Hohenemser, K. H.

Five alternative configurations for large horizontal axis wind turbines are considered that do not have a yaw gear drive. The rotor is either self-centering or where the yaw angle is controlled by blade cyclic pitch control. A preliminary evaluation of the dynamic characteristics for these alternative design configurations is presented. Lifting rotor technology, similar to that employed in helicopters, appears to promise superior, simpler, and cheaper solutions, probably by a wide margin.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 391-409.

**ATMOSPHERIC TURBULENCE PARAMETERS FOR MODELING WIND TURBINE DYNAMICS**  
Holley, W. E. , and Thresher, R. W.

This paper presents a model of the response of wind turbines to atmospheric turbulence developed using linearized aerodynamics for a three-bladed rotor and accounting for three turbulent velocity components as well as velocity gradients across the rotor disk. Typical response power spectral densities are shown. An equation error method, which can be used to estimate required parameters from field data, is also presented.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 101-112.

**WIND TURBULENCE INPUTS FOR HORIZONTAL AXIS WIND TURBINES**  
Holley, W. E. , Thresher, R. W. , and Lin, S-R.

This paper presents models of the important atmospheric sources for the force excitations felt by a HAWT system. The wind turbulence field is characterized by a three-dimensional velocity vector which varies randomly with time and with position in space. Considerable simplifications are presented in order to develop a practical analysis tool from the complete statistical description of this turbulent velocity field. The latter would require the determination of all possible joint probability distributions between different velocity components at different positions in space. (See companion paper by Thresher, Holley, and Jafarey at same conference.)

NASA-TT-F-15,522, 1974, Technical Translation.

**WIND ELECTRIC POWER STATION**  
Honnef, H.

NASA-TT-F-15,455, 1974, Technical Translation.

**WIND POWER TURBOGENERATOR FOR HIGH ALTITUDE WIND UTILIZATION**  
Honnef, H.

NASA-TT-F-15,444, 1974, Technical Translation.

**HIGH WIND POWER PLANTS**  
Honnef, H.

Chapter 7 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York), pp. 323-370.

**WIND TURBINE ACOUSTICS**

Hubbard, H. H. , and Shepherd, K. P.

This chapter summarizes available information on the physical characteristics of the noise generated by wind turbines and includes example sound pressure time histories, narrow-band and broadband frequency spectra, and noise radiation patterns. Also reviewed are noise measurement standards, analysis technology, and methods for characterizing and predicting the intensity of noise from wind turbines, both singly and in clusters. Atmospheric propagation data are included that illustrate the effects of distance and the effects of refraction caused by a vertical gradient in the mean wind speed. Perception thresholds for humans are defined for both narrow-band and broadband spectra from systematic tests in the laboratory and from observations in the field. Also summarized are structural vibrations and interior sound pressure levels, which could result from the low-frequency noise excitation of buildings.

91N16679 NASA-TP-3057 DOE/NASA/20320-77

**WIND TURBINE ACOUSTICS**

Hubbard, H. H. , and Shepherd, K. P.

Available information on the physical characteristics of the noise generated by wind turbines is summarized, with example sound pressure time histories, narrow- and broadband frequency spectra, and noise radiation patterns. Reviewed are noise measurement standards, analysis technology, and a method of characterizing wind turbine noise. Prediction methods are given for both low-frequency rotational harmonics and broadband noise components. Also included are atmospheric propagation data showing the effects of distance and refraction by wind shear. Human perception thresholds, based on laboratory and field tests, are given. Building vibration analysis methods are summarized. The bibliography of this report lists technical publications on all aspects of wind turbine acoustics.

NASA-TM-100528, 1988.

**WIND TURBINE ACOUSTICS RESEARCH -- BIBLIOGRAPHY WITH SELECTED ANNOTATION**

Hubbard, H. H. , and Shepherd, K. P.

NASA-CR-172427, 1984.

**ACOUSTIC TESTS OF THE MOD-0/5A WIND TURBINE ROTOR WITH TWO DIFFERENT AILERONS**

Hubbard, H. H. , and Shepherd, K. P.

NASA-CR-172292, 1984.

**THE EFFECTS OF BLADE MOUNTED VORTEX GENERATORS ON THE NOISE FROM A MOD-2 WIND TURBINE GENERATOR**

Hubbard, H. H. , and Shepherd, K. P.

NASA-CR-166124, 1983.

**MEASUREMENTS AND OBSERVATIONS OF NOISE FROM A 4.2 MEGAWATT (WTS-4) WIND TURBINE GENERATOR**

Hubbard, H. H. , and Shepherd, K. P.

Journal, Noise Control Engineering, Volume 21, No. 1, 1983, pp. 21-29.

**NOISE CHARACTERISTICS OF LARGE WIND TURBINE GENERATORS**

Hubbard, H. H. , Grosveld, F. W. , and Shepherd, K. P.

NASA-CR-166052, 1982.

**NOISE MEASUREMENTS FOR SINGLE AND MULTIPLE OPERATION OF 50 kW WIND TURBINE GENERATORS**

Hubbard, H. H. , and Shepherd, K. P.

NASA-CR-165856, 1982.

**SOUND MEASUREMENTS AND OBSERVATIONS OF THE MOD-0A WIND TURBINE GENERATOR**

Hubbard, H. H. , and Shepherd, K. P.

NASA-CR-165810, 1981.

**BROAD BAND SOUND FROM WIND TURBINE GENERATORS**

Hubbard, H. H. , Shepherd, K. P. , and Grosveld, F. W.

NASA-CR-165752, 1981.

**SOUND MEASUREMENTS OF THE MOD-2 WIND TURBINE GENERATOR**

Hubbard, H. H. , and Shepherd, K. P.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 123-129.

**ENERGY STORAGE USING HIGH-PRESSURE ELECTROLYSIS AND METHODS FOR RECONVERSION**

Hughes, W. L.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp.89-102.

**SPECIFICATION, SITING, AND SELECTION OF LARGE WECS PROTOTYPES**

Hugosson, S.

The Swedish Wind Energy Programme was started in 1974 with preliminary feasibility studies which indicated that wind power could become economic in Sweden and technical problems would not be unsurmountable. In 1975 a contract was given to Saab-Scania Company to design and install a semi-scale Wind Power Research Unit to study technical problems associated with wind turbine development. This paper documents the development of specifications for follow-on prototype turbines of megawatt scale, the request for proposal, and selection criteria, and looks forward to announcing the winners of the prototype wind turbine development contracts.

**79A20829** NASA-TM-79034 DOE/NASA/1004-78/14, 1978; also Proceedings, 23rd National SAMPE Symposium and Exhibition, 1978, Society for the Advancement of Material and Process Engineering, pp. 457-478.

**AN OPERATING 200-kW HORIZONTAL AXIS WIND TURBINE**

Hunnicutt, C. L. , Linscott, B. , and Wolf, R. A.

The Mod-0A wind turbine blades were rotated for the first time on November 30, 1977, establishing the Mod-0A as the first wind-driven generator in 35 years to be continuously tied into an electrical power system which services a community. Tower-mounted equipment and blade structural design and fabrication are discussed. Output from the 200-kilowatt machine will be enough to meet the power requirements of about 60 families. The experimental wind turbine generator (WTG) is a two-bladed, horizontal-axis, rotor system driving a synchronous electric generator through a step-up gear box located within a nacelle. The nacelle is mounted on top of a 100-foot tower with the rotor located downwind from the tower. The 200-kilowatt rated power output of the wind turbine is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph. Attention is given to operational details, aspects of blade design, blade fabrication, the use of strain gages, questions of aeroelastic stability, and an early analysis of test data.

NASA-TT-F-16,195, 1975, Technical Translation.

**WIND POWER MACHINES**

Hütter, U.

NASA-TT-F-15,822, 1974, Technical Translation.

**CONTRIBUTION TO GAIN BASIC DESIGN CONCEPTS FOR WIND POWER PLANTS**

Hütter, U.

NASA-TT-F-15,184, 1973, Technical Translation.

**INFLUENCE OF WIND FREQUENCY ON ROTATIONAL SPEED ADJUSTMENTS OF WINDMILL GENERATORS**

Hütter, U.

NASA-TT-F-15,068, 1973, Technical Translation.

**OPERATING EXPERIENCE OBTAINED WITH A 100-kW WIND POWER PLANT**

Hütter, U.

NASA-TT-F-15,050, 1973, Technical Translation.

**THE DEVELOPMENT OF WIND POWER INSTALLATIONS FOR ELECTRICAL POWER GENERATION IN GERMANY**

Hütter, U.

NASA-TT-F-14,879, 1973, Technical Translation.

**A WIND TURBINE WITH A 34-m ROTOR DIAMETER**

Hütter, U.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 19-22.

**PAST DEVELOPMENTS OF LARGE WIND GENERATORS IN EUROPE**

Hütter, U.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 206-207.

**SOME EXTEMPORANEOUS COMMENTS ON OUR EXPERIENCES WITH TOWERS FOR WIND GENERATORS**  
Hütter, U.

**79A15574** In Power System Control and Protection, 1978, Academic Press (New York) pp. 239-259.

**CONTROL OF WIND TURBINE GENERATORS CONNECTED TO POWER SYSTEMS**

Hwang, H. H. , Mozeico, H. V. , and Gilbert, L. J.

A unique simulation model based on a Mode-O wind turbine is developed for simulating both speed and power control. An analytical representation for a wind turbine that employs blade pitch angle feedback control is presented, and a mathematical model is formulated. For Mod-0 serving as a practical case study, results of a computer simulation of the model as applied to the problems of synchronization and dynamic stability are provided. It is shown that the speed and output of a wind turbine can be satisfactorily controlled within reasonable limits by employing the existing blade pitch control system under specified conditions. For power control, an additional excitation control is required so that the terminal voltage, output power factor, and armature current can be held within narrow limits. As a result, the variation of torque angle is limited even if speed control is not implemented simultaneously with power control. Design features of the ERDA/NASA 100-kW Mod-0 wind turbine are included.

**78A30196** IEEE PAPER F 77; also IEEE Transactions on Power Apparatus and Systems, Volume PAS-97, March-April 1978, pp. 536-544.

**SYNCHRONIZATION OF WIND TURBINE GENERATORS AGAINST AN INFINITE BUS UNDER GUSTING WIND CONDITIONS**

Hwang, H. H. , and Gilbert, L. J.

Studies of synchronizing a wind turbine generator against an infinite bus are performed on a digital computer. In the digital simulation, wind gusts of different magnitudes and durations are hypothesized. Prior to the synchronization, differences of the frequency and phase position between voltages of the alternator and the bus are also included in the simulation. Solutions for rotor speed, generator power angle, electromagnetic torque, wind turbine torque, wind turbine blade pitch angle, and armature current are simulated and presented graphically. The ERDA-NASA 100-kW wind turbine is used as a case study. The results so obtained will thus have immediate applications.

**77A32243** and **77N19580** NASA-TM-X-73613; also Proceedings, Control of Power Systems Conference and Exposition, 1977 (College Station, Texas). , 16 pp.

**SYNCHRONIZATION OF THE ERDA-NASA 100 KW WIND TURBINE GENERATOR WITH LARGE UTILITY NETWORKS**

Hwang, H. H. , and Gilbert, L. J.

The synchronizing of a wind turbine generator against an infinite bus under random conditions is studied for the first time. With a digital computer, complete solutions for rotor speed, generator power angle, electromagnetic torque, wind turbine torque, wind turbine blade pitch angle, and armature current are obtained and presented by graphs. Experiments have been recently performed on the ERDA-NASA 100 kW wind turbine. Experimental results matched computer study results very closely and confirmed that the synchronization can be accomplished by means of the existing speed control system and an automatic synchronizer.

**76N30650** NASA-TM-X-73459

**TRANSIENT ANALYSIS OF UNBALANCED SHORT CIRCUITS OF THE ERDA-NASA 100 KW WIND TURBINE ALTERNATOR**

Hwang, H. H. , and Gilbert, L. J.

Unbalanced short-circuit faults on the alternator of the ERDA-NASA Mod-0 100-kW experimental wind turbine are studied. For each case, complete solutions for armature, field, and damper-circuit currents; short-circuit torque; and open-phase voltage are derived directly by a mathematical analysis. Formulated results are tabulated. For the Mod-0 wind turbine alternator, numerical calculations are given, and results are presented by graphs. Comparisons for significant points among the more important cases are summarized. For these cases the transients are found to be potentially severe. The effect of the alternator neutral-to-ground impedance is evaluated.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), p. 195; Abstract.

**WAKE CHARACTERISTICS OF THE MOD-2 WIND TURBINE AT MEDICINE BOW, WYOMING**

Jacobs, E. W. , Kelley, N. D. , McKenna, H. E. , and Birkenheuer, N. J.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 155-158.

**EXPERIENCE WITH JACOBS WIND-DRIVEN ELECTRIC GENERATING PLANT**

Jacobs, M. L.

**84N14586** NASA-TM-83532 NASA/DOE/20320-56, 1983; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 795-801.

**USE OF THE WEST-1 WIND TURBINE SIMULATOR TO PREDICT BLADE FATIGUE LOAD DISTRIBUTION**  
Janetzke, D. C.

To test the ability of WEST-1 to predict blade fatigue load distribution, actual wind signals were fed into the simulator and the response data were recorded and processed in the same manner as actual wind turbine data. The WEST-1 simulator was operated in a stable, unattended mode for six hours. The probability distribution of the cyclic flatwise bending moment for the blade was comparable to that for an actual wind turbine in winds with low turbulence. The input from a stationary anemometer was found to be inadequate for use in the prediction of fatigue load distribution for blade design purposes and modifications are necessary.

**82N23707** Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 201-210.

**WHIRL FLUTTER ANALYSIS OF A HORIZONTAL-AXIS WIND TURBINE WITH A TWO-BLADED TEETERING ROTOR**

Janetzke, D. C. , and Kaza, K. R. V.

Whirl flutter and the effect of pitch-flap coupling on teetering motion of a wind turbine were investigated. The equations of motion are derived for an idealized five-degree-of-freedom mathematical model of a horizontal-axis wind turbine with a two-bladed teetering rotor. The model accounts for the out-of-plane bending motion of each blade, the teetering motion of the rotor, and both the pitching and yawing motions of the rotor support. Results show that the design is free from whirl flutter. Selected results are presented indicating the effect of variations in rotor support damping, rotor support stiffness, and pitch-flap coupling on pitching, yawing, teetering, and blade bending motions.

DOE/2521-1 E(49-18)-2521, 1977.

**SUMMARY OF CURRENT COST ESTIMATES OF LARGE WIND ENERGY SYSTEMS**

JBF Scientific Corporation

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 9-18.

**AERODYNAMIC PERFORMANCE PREDICTION OF HORIZONTAL AXIS WIND TURBINES**

Jeng, D. R. , Keith, T. G. , and Aliakbarkhanafteh, A.

A new procedure, called the helical vortex method, is described for calculating HAWT aerodynamic performance. Local induced velocities are calculated directly, and a specified circulation distribution is not required. Results of the proposed method are shown to agree well with experimental data, without some of the numerical difficulties encountered by the PROP Code when wind velocities are low.

NASA-CR-174910, 1985.

**DESIGN OF TEST SPECIMENS AND PROCEDURES FOR GENERATING MATERIAL PROPERTIES OF DOUGLAS FIR/EPOXY LAMINATED WOOD COMPOSITE MATERIAL; WITH THE GENERATION OF BASELINE DATA AT TWO ENVIRONMENTAL CONDITIONS**

Johnson, P. E.

Proceedings, Windpower '87 Conference, 1987, American Wind Energy Association (Washington, DC), SERI/CP-217-3315, National Renewable Energy Laboratory (Golden, Colorado), pp. 1-6.

**DESIGN, CONSTRUCTION AND EARLY OPERATION OF THE 3.2-MW MOD-5B WIND TURBINE**

Johnson, W. R.

This paper summarizes recent activities including installation of the 320-ft diameter Mod-5B near Kahuku on Oahu in

the Hawaiian Islands following shipment of all major components by barge from the mainland. Nacelle and rotor lifts were completed in April 1987, with first rotation achieved on July 1, 1987. Preliminary results of operating and performance tests are presented. Upon completion of testing, the turbine will sold to Hawaiian Electric Industries which will operate it as part of the 12.2-MW Kahuku commercial wind power station.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 604-609.

#### **STATUS OF THE DOI SVU WIND TURBINE PROJECT**

Johnson, W. R. , and Young, W. R.

This paper summarizes the operating experience and performance of the two system verification HAWTs at Medicine Bow, Wyoming: A 4-MW WTS-4 turbine with a 78-meter downwind rotor, and a 2.5-MW Mod-2 turbine with a 91-meter upwind rotor. Since 1982 both units have been successfully operated to evaluate the technical and economic feasibility of integrating a proposed 100-MW wind power station with existing hydroelectric facilities. Mechanical problems, mostly unforeseen, are described which have significantly reduced the operating times of both units below that anticipated. No incompatibilities between wind turbines and the electrical system have been observed.

85N29365 NASA-TM-86983 DOE/NASA/20320-63, 1985.

#### **GOVERNMENT REVIEW OF THE MOD-2 WIND TURBINE (AS-BUILT)**

Johnson, W. R. , Birchenough, A. G. , Linscott, B. S. , Reagan, J. R. , Sirocky, P. J. , Sizemore, R. L. , Sullivan, T. L. , and Holeman, R. H.

The findings and recommendations of the Government committee formed to conduct an as-built review of the three Mod-2 wind turbine units at Goldendale, Washington are given. The purpose of the review was to identify any critical deficiencies in machine components that could result in failure, and to recommend any necessary corrective action before resuming safe machine operation. The review concluded that one of the deficiencies identified would preclude planned attended or unattended operation, provided that certain corrective actions were implemented.

NASA-TM-82717 DOE/NASA/20305-6, 1981.

#### **RELIABILITY AND QUALITY ASSURANCE ON THE MOD-2 WIND SYSTEM**

Jones, B. G. , and Mason, W. E. B.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 95-101.

#### **ANALYTICAL TESTING TECHNIQUES**

Jones, R.

Structural-dynamic analytical testing techniques can be a tool to determine the source of structural dynamic problems and the solution to these problems. Analytical testing techniques are based upon new and unique dynamic testing methods and analysis of test results. Thus, these methods apply primarily to constructed wind turbine systems.

NASA-TT-F-15,860, 1974, Technical Translation.

#### **ARE WIND-DRIVEN POWER PLANTS POSSIBLE?**

Juchem, P.

NASA-TT-F-15,355, 1974, Technical Translation.

#### **THE CURRENT STATUS OF HONNEF WIND POWER PLANTS**

Juchem, P.

NASA-TT-F-15,516, 1974, Technical Translation.

#### **SUPPLEMENT TO THE REPORT ON THE RESULTS ACHIEVED WITH SEAS' EXPERIMENTAL MILL**

Juul, J.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 133-141.

#### **CHARACTERISTICS OF FUTURE VERTICAL AXIS WIND TURBINES (VAWTS)**

Kadlec, E.

As a DOE facility, Sandia laboratories is developing Darrieus VAWT technology whose ultimate objective is

economically feasible, industry-produced, commercially-marketed wind energy systems. This report presents the characteristics of current VAWT technology and designs and assesses their cost-effectiveness. The first full cycle of development of VAWTs is complete, and first-level aerodynamic, structural, and system analyses have evolved to support and evaluate complete system designs. Potential improvements identified in this first cycle are also presented along with their cost benefits.

NASA-CR-134934, 1976.

**DESIGN STUDY OF WIND TURBINES, 50 kW to 3000 kW FOR ELECTRIC UTILITY APPLICATIONS, SUMMARY REPORT**

Kaman Aerospace Corporation (Bloomfield, Connecticut)

NASA-CR-134936 ERDA/NASA/19404-76/2, 1977.

**DESIGN STUDY OF WIND TURBINES, 50 kW to 3000 kW FOR ELECTRIC UTILITY APPLICATIONS, VOLUME I: EXECUTIVE SUMMARY**

Kaman Aerospace Corporation (Bloomfield, Connecticut)

NASA-CR-134937 ERDA/NASA/19404-76/2 KAMAN Report R-1382, 1977.

**DESIGN STUDY OF WIND TURBINES, 50 kW TO 3000 kW FOR ELECTRIC UTILITY APPLICATIONS, VOLUME II: ANALYSIS AND DESIGN**

Kaman Aerospace Corporation (Bloomfield, Connecticut)

NASA-CR-168107, 1982.

**STABILITY ANALYSIS OF FLEXIBLE WIND TURBINE BLADES USING FINITE ELEMENT METHOD**

Kamoulakos, A.

NASA-CR-159502 DOE/NASA/3139-1, 1980.

**NONLINEAR AEROELASTIC EQUATIONS OF MOTION OF TWISTED, NONUNIFORM, FLEXIBLE HORIZONTAL-AXIS WIND TURBINE BLADES**

Kaza, K. R. V.

**79A29007 and 79N21549** NASA-TM-79101 DOE/NASA/1028-72/2 AIAA Paper 79-0733, 1979; also Proceedings, 20th Structures, Structural Dynamics, and Materials Conference, 1979, American Institute of Aeronautics and Astronautics (New York), pp. 53-63.

**EVALUATION OF MOSTAS COMPUTER CODE FOR PREDICTING DYNAMIC LOADS IN TWO-BLADED WIND TURBINES**

Kaza, K. R. V. , Janetzke, D. C. , and Sullivan, T. L.

Calculated dynamic blade loads were compared with measured loads over a range of yaw stiffness of the DOE/NASA Mod-0 wind turbine to evaluate the performance of two versions of the MOSTAS computer code. The first version uses a time-averaged coefficient approximation in conjunction with a multi-blade coordinate transformation for two bladed rotors to solve the equations of motion by standard eigenanalysis. The second version accounts for periodic coefficients while solving the equations by a time history integration. A hypothetical three-degree of freedom dynamic model was investigated. The exact equations of motion of this model were solved using the Floquet-Lipunov method. The equations with time-averaged coefficients were solved by standard eigenanalysis. The results obtained with this approximate analysis do not agree with dynamic blade load amplifications at or close to resonance conditions. The results of the second version, which accounts for periodic coefficients while solving the equations by a time history integration, compare well with the measured data.

NASA-TM-79295 DOE/NASA/1028-79/25, 1979.

**AEROELASTIC EQUATIONS OF MOTION OF A DARRIEUS VERTICAL-AXIS WIND-TURBINE BLADE**

Kaza, K. R. V. , and Kvaternik, R. G.

NASA-TM-74059, 1977.

**NONLINEAR AEROELASTIC EQUATIONS FOR COMBINED FLAPWISE BENDING, CHORDWISE BENDING, TORSION, AND EXTENSION OF TWISTED NONUNIFORM ROTOR BLADES IN FORWARD FLIGHT**

Kaza, K. R. V. , and Kvaternik, R. G.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 61-69.

#### **AEROELASTIC STABILITY OF WIND TURBINE BLADES**

Kaza, K. R. V.

The second-degree nonlinear aeroelastic equations for a flexible, twisted, non-uniform wind turbine blade are developed using Hamilton's principle. The derivation of these equations has its basis in the geometric nonlinear theory of elasticity. These equations with periodic coefficients are suitable for determining the aeroelastic stability and response of large wind turbine blades. Methods for solving these equations are discussed.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 447-454.

#### **AERODYNAMIC PERFORMANCE PREDICTION OF A TIP-CONTROLLED HORIZONTAL AXIS WIND TURBINE**

Keith, T. G. Jr. , White, J. A. , and Jeng, D. R.

A modified version of a vortex method for propeller analysis is used, accounting for the lost lift effect that occurs at the blade-to-tip gap and the drag of the tip spindle. A simplified, linear method is also presented, which provides results that are in close agreement with the non-linear approach in a fraction of the computing time. Calculated power curves are compared with experimental data from the 125-ft diameter Mod-0 experimental wind turbine operating at various speeds.

81N11448 NASA-TM-81588 DOE/NASA/1028-27, 1980.

#### **PERFORMANCE OF A STEEL SPAR WIND TURBINE BLADE ON THE MOD-0 100 KW EXPERIMENTAL WIND TURBINE**

Keith, T. G. Jr. , Sullivan, T. L. , and Viterna, L. A.

The performance and loading of a large wind rotor, 38.4 m in diameter and composed of two low-cost steel spar blades were examined. Two blades were fabricated at Lewis Research Center and successfully operated on the Mod-0 wind turbine at Plum Brook. The blades were operated on a tower on which the natural bending frequency were altered by placing the tower on a leaf-spring apparatus. It was found that neither blade performance nor loading were affected significantly by this tower softening technique. Rotor performance exceeded prediction while blade loads were found to be in reasonable agreement with those predicted. Seventy-five hours of operation over a five month period resulted in no deterioration in the blade.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 221-228.

#### **OBSERVED ACOUSTIC AND AEROELASTIC SPECTRAL RESPONSES OF A MOD-2 TURBINE BLADE TO TURBULENCE EXCITATION**

Kelley, N. D. , McKenna, H. E. , and Jacobs, E. W.

Preliminary results are discussed of an experiment designed to directly evaluate the acoustic/aeroelastic spectral responses of a large-scale HAWT blade to turbulence-induced unsteady air loads. The experimental procedure consisted of flying a hot-film anemometer from a tethered balloon in the turbine inflow and simultaneously measuring the aeroelastic responses and fluctuating air loads at two blade spanwise locations. The latter measurements were made using surface-mounted, subminiature pressure transducers. The radiated acoustic pressure field was also measured with an array of very-low-frequency microphones installed at ground level, 1.5-rotor diameters upwind. Initial estimates are presented of transfer functions for full-disk acoustic radiation, blade normal forces, and chordwise/flatwise blade bending moments.

SERI/TR-635-1240, 1983, National Renewable Energy Laboratory (Golden, Colorado).

#### **ACOUSTICAL MEASUREMENTS OF DOE/NASA MOD-0 WIND TURBINE AT PLUM BROOK STATION, OH**

Kelley, N. D. , McKenna, H. E. , Etter, C. L. , Garrelts, R. , and Linn, C.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 701-708.

#### **AERODYNAMIC SOURCES OF ACOUSTIC RADIATION FROM A SINGLE MOD-2 WIND TURBINE**

Kelley, N. D. , Hemphill, R. R. , and McKenna, H. E.

Results are presented of an extensive acoustic measurement program conducted around one of the three 2.5-MW Mod-2 HAWTs at the Goodnoe Hills test site near Goldendale, Washington, including a summary of low-frequency acoustic emission characteristics. Mod-2 emissions are compared with two other HAWTs and one VAWT. The unsteady aerodynamic forcing, in response to certain freestream turbulence characteristics, is identified as the source of observed acoustic and rotor aeroelastic responses.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 375-387.  
**ACOUSTIC NOISE GENERATION BY THE DOE/NASA MOD-1 WIND TURBINE**  
 Kelley, N. D.

Measurements of the acoustic emissions from the Mod-1 HAWT have shown that the maximum acoustic energy is concentrated in the low-frequency range, often below 100 Hz. Coherent sounds from this turbine are usually impulsive and are identified as the principal source of the annoyance to a dozen families living within 3 km of the site. The source of the coherent noise appears to be the rapid change in blade loads encountered as a blade passes through the wake of the tower. Peak levels of these impulses can be enhanced or subdued through complex propagation effects and interactions with structural modes of homes.

91A31064 and 90N12034 NASA-TM-102378 DOE/NASA/20320-23; also Proceedings, 1990 Annual Reliability and Maintainability Symposium, 1990, Institute of Electrical and Electronics Engineers (New York) pp. 337-340.  
**MODEL-0A WIND TURBINE GENERATOR - FAILURE MODES AND EFFECTS ANALYSIS**  
 Klein, W. E. , and Lali, V. R.

The results of failure modes and effects analysis (FMEA) conducted for wind-turbine generators are presented. The FMEA was performed for the functional modes of each system, subsystem, or component. The single-point failures were eliminated for most of the systems. The blade system was the only exception. The qualitative probability of a blade separating was estimated at level D-remote. Many changes were made to the hardware as a result of this analysis. The most significant change was the addition of the safety system. Operational experience and need to improve machine availability have resulted in subsequent changes to the various systems, which are also reflected in this FMEA.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 67-76.  
**RECENT DARRIEUS VERTICAL AXIS WIND TURBINE AERODYNAMICAL EXPERIMENTS AT SANDIA NATIONAL LABORATORIES**  
 Klimas, P. C.

Results of aerodynamic tests on VAWT blades are described, including chordwise pressure surveys; circumferential blade acceleration surveys; measurements of the effects of blade camber, pitch, and offset; and the use of profiles designed specifically for VAWT applications.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 37-45.  
**G.E. SYSTEMS STUDIES OF LARGE-SCALE WECS**  
 Killen, R.

82N19550 NASA-TM-82803 DOE/NASA/20320-38 Revised, 1982; also Proceedings, Ninth Annual Engineering Conference on Reliability, 1982.  
**EXPERIENCE WITH MODIFIED AEROSPACE RELIABILITY AND QUALITY ASSURANCE METHOD FOR WIND TURBINES**  
 Klein, W. E.

The SR&QA approach assures that the machine is not hazardous to the public or operating personnel, can operate unattended on a utility grid, demonstrates reliability operation, and helps establish the quality assurance and maintainability requirements for future wind turbine projects. The approach consisted of modified failure modes and effects analysis (FMEA) during the design phase, minimal hardware inspection during parts fabrication, and three simple documents to control activities during machine construction and operation. Five years experience shows that this low cost approach works well enough that it should be considered by others for similar projects.

80A40335 and 80N13490 NASA-TM-79284 DOE/NASA/20370-79/18, 1980; also Proceedings, 1980 Annual Reliability and Maintainability Symposium, 1980, Institute of Electrical and Electronics Engineers (New York) pp. 254-258.  
**MODIFIED AEROSPACE R&QA METHOD FOR WIND TURBINES**  
 Klein, W. E.

This paper describes the Safety, Reliability and Quality Assurance (SR&QA) approach developed for the first large wind turbine generator project, Mod-0A. The SR&QA approach to be used had to assure that the machine would not be hazardous, would operate unattended on a utility grid, would demonstrate reliable operation, and would help establish the quality assurance and maintainability requirements for wind turbine projects. The final approach consisted of a modified Failure Modes and Effects Analysis (FMEA) during the design phase, minimal hardware inspections during parts fabrication, and three

documents to control activities during machine construction and operation.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111. pp. 121-131.

#### **LARGE WIND ENERGY CONVERTER -- GROWIAN 3 MW**

Körber, F. and Thiele, H. A.

This 100-m diameter turbine atop a 100-m tower is the largest wind power unit ever to be built. Distinctive features of its design, performance analysis, and construction plans are discussed. It is expected to be in operation in two and one-half years.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752,  
pp. 689-708.

#### **THE 80 MEGAWATT WIND POWER PROJECT AT KAHUKU POINT, HAWAII**

Laessig, R. R.

This paper describes plans for the development of one of the largest wind power stations in the world, on a 2,100 acre site on the northern tip of the island of Oahu. The developer, Windfarms Ltd. , has selected twenty WTS-4 HAWTs for use in this project, each rated at 4 MW. Topics discussed are land acquisition, power purchase agreement, meteorological work, buildings, transmission of power, environmental impact statement, and costs and schedule. Other projects are described briefly, on the island of Hawaii and in Solano County, California. Desirable features of future wind turbines are presented from the developers point of view.

**83N27347** NASA-TM-83323 DOE/NASA/20320-45, 1983

#### **FABRICATION OF LOW-COST MOD-0A WOOD COMPOSITE WIND TURBINE BLADES**

Lark, R. F. , Gougeon, M. , Thomas, G. , and Zuteck, M. D.

The wood composite blades were fabricated by using epoxy resin-bonded laminates of Douglas fir veneers for the leading edge spar sections and honeycomb-cored birch plywood panels for the blade trailing edge or afterbody sections. The blade was joined to the wind turbine hub assembly by epoxy resin-bonded steel load take-off studs. The wood composite blades were installed in the Mod-0A wind turbine test facility at Kahuku, Hawaii. The wood composite blades have successfully completed high power (average of 150 kW) operations for an eighteen month period (nearly 8,000 hr) before replacement with another set of wood composite blades. The original set of blades was taken out of service because of the failure of the shank on one stud. An inspection of the blades at NASA-Lewis showed that the shank failure was caused by a high stress concentration at a corrosion pit on the shank fillet radius which resulted in fatigue stresses in excess of the endurance limit.

**83N16857** NASA-TM-83046 DOE/NASA/20320-43, 1983; also Proceedings, 28th National SAMPE Symposium and Exposition, 1983, Society for the Advancement of Material and Process Engineering, pp. 457-478.

#### **CONSTRUCTION OF LOW-COST, MOD-0A WOOD COMPOSITE WIND TURBINE BLADES**

Lark, R. F.

Two sixty-foot, low-cost, wood composite blades for service on 200 kW Mod-0A wind turbines were constructed. The blades were constructed of epoxy resin-bonded Douglas fir veneers for the leading edge sections, and paper honeycomb-cored, birch plywood faced panels for the afterbody sections. The blades were joined to the wind turbine hub by epoxy resin-bonded steel load take-off studs embedded into the root end of the blades. The blades were installed on the 200 kW Mod-0A wind turbine facility at Kahuku, Hawaii. The blades completed nearly 8,000 hours of operation over an 18 month period at an average power of 150 kW prior to replacement with another set of wood composite blades. The blades were replaced because of a corrosion failure of the steel shank on one stud. Inspections showed that the wood composite structure remained in excellent condition.

**83N15362** NASA-TM-83044; also Proceedings, 38th Annual Conference of the Society of Plastics Industry (SPI) Reinforced Plastics/Composites Institute, 1983.

#### **HYGROTHERMOMECHANICAL EVALUATION OF TRANSVERSE FILAMENT TAPE EPOXY/POLYESTER FIBERGLASS COMPOSITES**

Lark, R. F. , and Chamis, C. C.

The static and cyclic load behavior of transverse filament tape (TFT) fiberglass/epoxy and TFT fiberglass/polyester composites, intended for use in the design of low-cost wind turbine blades, are presented. The data behavior is also evaluated with respect to predicted properties based on an integrated hygrothermomechanical response theory. Experimental TFT composite data were developed by the testing of laminates made by using composite layups typical of those used for the

fabrication of TFT fiberglass wind turbine blades. Static properties include tension, compression, and interlaminar shear strengths at ambient conditions and at high humidity/elevated temperature conditions after a 500 hour exposure. Cyclic fatigue data were obtained using similar environmental conditions and a range of cyclic stresses. The environmental (temperature and moisture) and cyclic load effects on composite strength degradation are subsequently compared with the predictions obtained by using the composite life/durability theory. The results obtained show that the predicted hygrothermomechanical environmental effects on TFT composites are in good agreement with measured data for various properties including fatigue at different cyclic stresses.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 159-164.

#### **REVIEW OF THE WINDPOWER ACTIVITIES AT THE BRACE RESEARCH INSTITUTE**

Laweand, T. A.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), pp. 197-208.

#### **INVESTIGATION OF WAKE OF 200-kW WIND TURBINE BY LASER DOPPLER VELOCIMETER (LDV)**

Lieblein, S. , and Eberle, W. R.

Tests to determine the capability of the LDV to provide useful data on wake development are described, which were conducted with the Mod-0A 200-kW wind turbine in Clayton, New Mexico. Free-stream conditions at the wake deduced from the LDV traces compared well with anemometer values. Well-defined wakes were observed when the turbulence level and the turbine power fluctuations were low. Dissipation of the wind speed deficit could have occurred in 8 to 10 rotor diameters. When turbulence and power fluctuations were high, LDV traces showed a large scatter and no wakes, for reasons not determined. Correlations are presented among the fluctuations in wind speed, wind direction, output power, and wind shear profile exponent.

NASA-CR-165320 DOE/NASA/9549-1, 1981.

#### **SURVEY OF LONG-TERM DURABILITY OF FIBERGLASS-REINFORCED PLASTIC STRUCTURES**

Lieblein, S.

**80N16453** Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, 457 pp; pp. 403-457 (Working Group Summaries, Panel Discussions, and Closure).

#### **LARGE WIND TURBINE DESIGN CHARACTERISTICS AND R AND D REQUIREMENTS**

Lieblein, S., Editor

Thirty-four detailed technical presentations (1) describe the characteristics and development status of current large wind turbines, (2) identify the technical problems that must be solved to achieve the cost goals, (3) identify and discuss promising solutions, and (4) describe the R&D efforts required to demonstrate the feasibility of the proposed solutions. Large wind turbine research and development activities sponsored by public and private organizations in the U.S. and three European countries are presented. Both horizontal and vertical axis machines are considered with emphasis on their structural design. Sessions included the development status of large-scale wind turbines, wind turbine blade design characteristics and operating experience, and special topics. Both prepared formal papers and edited transcriptions of panel discussions, working-group summaries, and questions and answers are included.

DOE/NASA/7653-79/1, 1979.

#### **EVALUATION OF URETHANE FOR FEASIBILITY OF USE IN WIND TURBINE BLADE DESIGN**

Leiblein, S. , Ross, R. S. , and Fertis, D. G.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 413-416.

#### **INNOVATIVE AND ADVANCED SYSTEM CONCEPTS**

Lissaman, P. B. S.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 208.

#### **WIND MACHINES**

Lissaman, P. B. S.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 11-18.

**PERCY THOMAS WIND GENERATOR DESIGNS**

Lines, C. W.

**84N27327** NASA-TM-83546 DOE/NASA/20320-58, 1984.

**LARGE, HORIZONTAL-AXIS WIND TURBINES**

Linscott, B. S. , Perkins, P. , Dennett, J. T.

Development of the technology for safe, reliable, environmentally acceptable large wind turbines that have the potential to generate a significant amount of electricity at costs competitive with conventional electric generating systems are presented. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements. There are several ongoing large wind system development projects and applied research efforts directed toward meeting the technology requirements for utility applications. Detailed information on these projects is provided. The Mod-0 research facility and current applied research effort in aerodynamics, structural dynamics and aeroelasticity, composite and hybrid composite materials, and multiple system interaction are described. A chronology of component research and technology development for large, horizontal axis wind turbines is presented. Wind characteristics, wind turbine economics, and the impact of wind turbines on the environment are reported. The need for continued wind turbine research and technology development is explored. Over 40 references are cited and a bibliography is included.

NASA-TM-82594, 1981.

**ALUMINUM BLADE DEVELOPMENT FOR THE MOD-0A 200-kW WIND TURBINE**

Linscott, B. S. , Shaltens, R. K. , and Eggers, A. G.

**83N70172** NASA-TM-82595 DOE/NASA/220370-21, 1981.

**TEST EXPERIENCE WITH ALUMINUM BLADES ON THE MOD-0A 200-KILOWATT WIND TURBINE AT CLAYTON, NEW MEXICO**

Linscott, B. S. , Shaltens, R. K. , and Eggers, A. G.

**83N31107** NASA-TM-83444 DOE/NASA/20320-47, 1983; also Proceedings, Wind/Solar Energy Conference (Kansas City, Missouri), 1983.

**DOE LARGE HORIZONTAL AXIS WIND TURBINE DEVELOPMENT AT NASA LEWIS RESEARCH CENTER**

Linscott, B. S.

Large wind turbine activities managed by NASA Lewis are reviewed. These activities include results from the first and second generation field machines (Mod-0A, -1, and -2), the status of the Department of Interior WTS-4 machine for which NASA is responsible for technical management, and the design phase of the third generation wind turbines (Mod-5).

**82N14633** NASA-TM-82594 DOE/NASA/20370-20, 1981.

**ALUMINUM BLADE DEVELOPMENT FOR THE MOD-0A 200-KILOWATT WIND TURBINE**

Linscott, B. S. , Shaltens, R. K. , and Eggers, A. G.

The rotor blade configuration, fabrication methods, analyses, operating experience, design modifications, and cost are described. Each 60-ft.(18.3-m) long aluminum blade used current aircraft fixed wing and rotary wing design and fabrication technologies. Structural damage, repairs, and modifications that occurred during 6500 hours of operation are summarized.

**81N27606** NASA-TM-82681 DOE/NASA/20305-5, 1981.

**THE MOD-2 WIND TURBINE DEVELOPMENT PROJECT**

Linscott, B. S. , Dennett, J. T. , and Gordon, L. H.

A major phase of the Federal Wind Energy Program, the Mod-2 wind turbine, a second-generation machine developed by the Boeing Engineering and Construction Co. for the U.S. Department of Energy and the Lewis Research Center of the National Aeronautics and Space Administration, is described. The Mod-2 is a large (2.5-MW power rating) horizontal-axis wind turbine designed for the generation of electrical power on utility networks. Three machines were built and are located in a cluster at Goodnoe Hills, Washington. All technical aspects of the project are described: design approach, significant innovation features, the mechanical system, the electrical power system, the control system, and the safety system.

**80N16470** Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 225-238.

**BLADE DESIGN AND OPERATING EXPERIENCE ON THE MOD-0A 200 KW WIND TURBINE AT CLAYTON, NEW MEXICO**

Linscott, B. S. , and Shaltens, R. K.

Two 60 foot long aluminum wind turbine blades were operated for over 3,000 hours on the MOD-0A wind turbine. The first signs of blade structural damage were observed after 400 hours of operation. Details of the blade design, loads, cost, structural damage, and repair are discussed.

**78N19642** NASA-TM-73883 DOE/NASA/1028-78/15, 1977; also 12th Intersociety Energy Conversion Engineering Conference, Volume 2, 1977, American Nuclear Society (La Grange Park, Illinois), pp. 1633-1650.

**EXPERIMENTAL DATA AND THEORETICAL ANALYSIS OF AN OPERATING 100 KW WIND TURBINE**

Linscott, B. S. , Glasgow, J. C. , Anderson, W. D. , and Donham, R. E.

Part of the cooperative effort between NASA and ERDA has been the design and the erection of an experimental wind turbine by the NASA-Lewis Research Center. This 100 kW turbine, designated the Mod-O, is located at the NASA Plum Brook site near Sandusky, Ohio. Experimental test data have been correlated with analyses of turbine loads and complete system behavior of the 100 kW Mod-O wind turbine generator over a broad range of steady state conditions, as well as during transient conditions. The deficit in the ambient wind field due to the upwind tower turbine support structure was found to be very significant in exciting higher harmonic loads associated with the flapping response of the blade in bending.

**76N33628** NASA-TM-X-3426 ERDA/NASA/1028-77/14, 1976.

**TOWER AND ROTOR BLADE VIBRATION TEST RESULTS FOR A 100-KILOWATT WIND TURBINE**

Linscott, B. S. , Shapton, W. R. , Brown, D.

The predominant natural frequencies and mode shapes for the tower and the rotor blades of the ERDA-NASA 100-kW wind turbine were determined. The tests on the tower and the blades were conducted both before and after the rotor blades and the rotating machinery were installed on top of the tower. The tower and each blade were instrumented with an accelerometer and impacted by an instrumented mass. The tower and blade structure was analyzed by means of NASTRAN, and computed values agree with the test data.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 191-198.

**VARIABLE SPEED GENERATOR TECHNOLOGY OPTIONS**

Lipo, T. A.

The rapid development of AC adjustable-speed drives has resulted in an array of alternatives which have potential application for wind turbines. This paper focuses on the options available, particularly for megawatt-scale turbines, and their advantages and disadvantages.

Chapter 6 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

**WIND TURBINE AIRFOILS AND ROTOR WAKES**

Lissaman, P. B. S.

Detailed characteristics of the lifting surfaces which we know as airfoils are discussed, in order to provide guidance in the selection of airfoil shapes that will perform satisfactorily over the broad operating environment of a wind turbine. The fundamental fluid-dynamic principles involved in modeling the structure of rotor wakes are presented, including the integration of wake-induced effects over an array of wind turbines.

PNL-4572 Report, 1983, Pacific Northwest Laboratories (Richland, Washington).

**WAKE STRUCTURE MEASUREMENTS AT THE MOD-2 CLUSTER TEST FACILITY AT GOODNOE HILLS**

Lissaman, P. B. S. , Zambrano, T. B. , and Gyatt, G. W.

Toledo University, 1985.

**APPLICATION OF A PERSONAL COMPUTER FOR THE UNCOUPLED VIBRATION ANALYSIS OF WIND TURBINE BLADE AND COUNTERWEIGHT ASSEMBLIES**

Little, R. R. , and White, P. R.

PNL-4535 Report, 1983, Pacific Northwest Laboratories (Richland, Washington).

**FLOW VISUALIZATION STUDY OF THE MOD-2 WIND TURBINE WAKE**

Liu, H-T. , *et al.*

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 89-98.

**A NASTRAN-BASED COMPUTER PROGRAM FOR STRUCTURAL DYNAMICS ANALYSIS OF HORIZONTAL-AXIS WIND TURBINES**

Lobitz, D. W.

Software is described that is based on the finite-element method through its reliance on NASTRAN for the development of mass, stiffness, and damping matrices of a HAWT tower and rotor as separate structures. The tower is modeled in a stationary frame of reference and the rotor in a frame of reference which is rotating at a constant angular speed. The two structures are subsequently joined together (external to NASTRAN) using a time-dependent transformation consistent with the hub configuration. Aerodynamic loads with aeroelastic effects are added and the resulting equations of motion are solved in the time domain using the implicit Newmark-Beta integrator. The requirements of versatility, accuracy, and speed have been satisfactorily met, to date.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 189-197.

**DYNAMIC ANALYSIS OF DARRIEUS VERTICAL AXIS WIND TURBINE ROTORS**

Lobitz, D. W.

Dynamic response characteristics of VAWT rotors are important factors governing safety and fatigue life. Principal problems are determining critical rotor speeds (resonances) and assessing the amplitudes of responses to forced vibrations, which are complicated by centrifugal and Coriolis effects. Primary tools for rotor analysis now in use at the Sandia National Laboratories are described, including a lumped spring-mass model (VAWTDYN) and also finite-element based approaches. Accuracy and completeness of current capabilities, and future plans are discussed.

NASA-TM-78927, 1978.

**PROPOSED DESIGN PROCEDURE FOR TRANSMISSION SHAFTING UNDER FATIGUE LOADING**

Loewenthal, S. H.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 440-445.

**DEVELOPMENT OF THE LOAD SPECTRUM FOR THE WESTINGHOUSE WWG-0600 WIND TURBINE**

Long, R. S.

Extensive loads analysis of this 600-kW commercial HAWT are summarized, which were performed using the REXOR II code containing aeroelastic structural models. Results include the effects of teetering, wind retardation, tower degrees of freedom, and three blade deformation modes. The effects on design loads of different shutdown scenarios and operating setpoints are presented. A NASA empirical model is used to introduce the effects of rotationally-sampled turbulence.

Proceedings, Seventh ASME Wind Energy Symposium, SED-Vol. 5, 1988, American Society of Mechanical Engineers (New York), pp. 71-75.

**PERFORMANCE TESTING OF WESTINGHOUSE WWG-0600 WIND TURBINE**

Long, S. E.

A review is presented of performance testing methods and data from two of the fifteen 142-ft diameter 600-kW HAWTs in the Kahuku wind power station on Oahu in the Hawaiian Islands. Emphasis is on data reduction and analysis. Performance testing, conducted in accordance with the ASME Performance Test Code for Wind Turbines, included developing a correlation between wind speeds at the hub and those measured at the meteorological tower during operations. Data reduction techniques using spreadsheet software are described, including test run listings and graphical analyses recommended for addition to the ASME Code calculation methods. For the same power output, test wind speeds were found to be over 1 mph lower than reference wind speeds.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 59-68.

**NORTHEAST UTILITIES' PARTICIPATION IN THE KAMAN/NASA WIND POWER PROGRAM**

Lotker, M.

Proceedings, Wind Energy Expo '83 and National Conference, 1983, American Wind Energy Association (Washington, DC), pp. 34-47.

#### **REVIEW OF THE MOD-2 AND MOD-5B WIND TURBINE PROJECTS**

Lowe, J. E.

This paper presents a summary of experiences to date with five Mod-2 2.5-MW HAWTs and the current status of the Mod-5B third-generation multi-megawatt wind turbine design. Three Mod-2 machines are near Goldendale, Washington, one near Medicine Bow Wyoming, and the fifth is located in Solano County and is the first sold to a private utility. These five turbines have operated on-line for over 5000 hours and generated over 6.5 million kilowatt hours.

Proceedings, Workshop on Economic and Operational Requirements and Status of Large-Scale Wind Systems, 1979, pp. 318-331.

#### **THE MOD-2 WIND TURBINE**

Lowe, J. E. , and Engle, W. W.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 229-236.

#### **ANECHOIC WIND TUNNEL STUDY OF TURBULENCE EFFECTS ON WIND TURBINE BROADBAND NOISE**

Loyd, B. , Wang, J. , and Harris, W. L.

This paper describes results obtained at MIT on the experimental and theoretical modelling of aerodynamic broadband noise generated by a HAWT with a downwind rotor, in which the noise is attributed to the interaction on ingested (*i.e.* , inflow) turbulence with the rotor blades. Turbulence was generated in the anechoic wind tunnel with the aid of biplanar grids of various sizes. The parameters of longitudinal integral scale of turbulence, the size scale of turbulence, the number of turbine blades, blade pitch, and free-stream velocity were varied. Sound pressure level was found to vary directly with the integral scale of the ingested turbulence but not with its intensity level. A theoretical model based on unsteady aerodynamics is proposed.

Chapter 4 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

#### **COMMERCIAL WIND TURBINES AND APPLICATIONS**

Lynette, R. , and Gipe, P.

This discussion of commercial systems and applications considers small-, medium-, and large-scale horizontal-axis wind turbines and medium-scale vertical-axis wind turbines in the U.S. and abroad. Included are windmills for water-pumping and wind turbines for generating electrical energy. Commercial systems are those which are production turbines, pre-production turbines that could be manufactured within five years, and prototype turbines that are privately owned and producing electricity for sale.

NASA-CR-159632 DOE/NASA/0002-79/1, 1979.

#### **MOD-2 FAILURE MODES AND EFFECTS ANALYSIS**

Lynette, R. , and Poore, R. Z.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 401-409.

#### **PREDICTIONS OF LOW-FREQUENCY AND IMPULSIVE SOUND RADIATION FROM HORIZONTAL-AXIS WIND TURBINES**

Martinez, R. , Widnall, S. E. , and Harris, W. L.

This paper develops theoretical models to predict the radiation of low-frequency and impulsive sounds from three sources in a HAWT, which are (1) steady blade loads, (2) unsteady blade loads from wind shear, and (3) unsteady loads on blades passing through the tower wake. These models are then used to calculate the acoustic output of the Mod-1 HAWT near Boone, North Carolina. Good agreement is obtained between calculated acoustic time signals and those measured near the Mod-1.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 187-193.

#### **DYNAMICS OF DRIVE SYSTEMS FOR WIND ENERGY CONVERSION**

Martinez-Sanchez, M.

Calculations are performed to determine the dynamic effects of mechanical power transmission from the nacelle of a horizontal axis wind machine to the ground or to an intermediate level. It is found that resonances are likely at 2 or 4/rev,

but they occur at low power only, and seem easily correctable. Large reductions are found in the harmonic torque inputs to the generator at powers near rated.

NASA-TT-F-15,433, 1974, Technical Translation.

#### **THE MEASUREMENT OF LARGE WIND ENERGY GENERATORS**

Martini, C.

**81N33492** NASA-TM-82717 DOE/NASA/20305-6; also Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. II, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 151-164.

#### **RELIABILITY AND QUALITY ASSURANCE ON THE MOD-2 WIND SYSTEM**

Mason, W. E. B. , and Jones, B. G.

The Safety, Reliability, and Quality Assurance (R&QA) approach developed for the largest wind turbine generator, the Mod 2, is described. The R&QA approach assures that the machine is not hazardous to the public or to the operating personnel, is operated unattended on a utility grid, demonstrates reliable operation, and helps establish the quality assurance and maintainability requirements for future wind turbine projects. The significant guideline consisted of a failure modes and effects analysis (FMEA) during the design phase, hardware inspections during parts fabrication, and three simple documents to control activities during machine construction and operation.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 353-356.

#### **INTEGRATION OF WIND TURBINE GENERATION (WTG) INTO UTILITY GENERATING SYSTEMS**

McCabe, T. F. , and Goldenblatt, M. K.

A summary is given of a study performed by JBF Scientific Corporation for the Pacific Northwest Laboratory, examining the sensitivity of utility cost of generation to both wind speed sampling frequency and wind turbine performance. The study uses two-minute wind speed data measured in 1979 at San Geronio Pass, California, and a simulation model of the 2.5-MW Mod-2 wind turbine. Preliminary results are listed.

AIAA-82-0282, 1982, American Institute of Aeronautics and Astronautics.

#### **DYNAMIC STALL -- COLLECTED PAPERS**

McCroskey, W. J. , *et al.*

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 783-800.

#### **ECONOMICS OF WIND ENERGY FOR UTILITIES**

McCabe, T. F. , and Goldenblatt, M. K.

This paper presents preliminary results from a study currently underway to establish the economic value of central station wind energy to certain specific utilities in terms of three parameters: Wind resource, mix of conventional generation sources, and financial factors including projected fuel costs. Economic value is derived from the total savings created as a result of reducing the need for conventional fuels and do not reflect any savings resulting from deferred or displaced conventional capacity. Results for six of the utilities studied are presented and compared.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 546-551.

#### **THE MOD-0 LARGE HORIZONTAL AXIS WIND TURBINE RESEARCH FACILITY**

McDade, J. , and Pfanner, H. G.

This paper describes the NASA/DOE Mod-0 wind turbine research facility near Sandusky, Ohio, designed and built as an integral part of the federal wind energy program in 1975. A summary is given of the wide variety of testing of turbine configurations and components that has taken place at this facility during the past 10 years. Topics discussed include a chronology of operational configurations of the basic 125-ft diameter 100-kW HAWT, structural and mechanical concepts tested, aerodynamic research, electrical generation systems, and environmental studies.

SERI/TR-635-967, 1982, National Renewable Energy Laboratory (Golden, Colorado).

**ENVIRONMENTAL NOISE LEVELS AT THE DOE MOD-2 WIND TURBINE LOCATED AT GOODNOE HILLS, WASHINGTON**

McKenna, H. E. , *et al.*

SERI/TR-635-967 and -1069, 1982, National Renewable Energy Laboratory (Golden, Colorado).

**ENVIRONMENTAL NOISE LEVELS AT THE SVU AND MOD-2 WIND TURBINE TEST SITES AT WPRS, MEDICINE BOW, WYOMING**

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 333-342.

**AUTOMATIC CONTROL ALGORITHM EFFECTS ON ENERGY PRODUCTION**

McNerney, G. M.

A computer model has been developed with actual wind time series and turbine performance data to simulate the power produced by the Sandia 17-m VAWT operating in automatic control, to investigate the influence of starting algorithms on annual energy production. Results indicate that, depending on turbine and local wind characteristics, an incorrect choice of the starting control algorithm can significantly reduce the overall energy production of this VAWT. An attempt is made to generalize these results to obtain guidelines for control algorithm design.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 46-58.

**CONCEPT SELECTION, OPTIMIZATION, AND PRELIMINARY DESIGN OF LARGE WIND GENERATORS**

Meier, R. C.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 424-430.

**STATUS REPORT ON DOWNWIND ROTOR HORIZONTAL AXIS WIND TURBINE NOISE PREDICTION**

Metzger, F. B. , and Klatte, R. J.

This report briefly summarizes work at Hamilton Standard in the following areas related to wind turbine noise: (1) Obtaining high-quality noise data under well-documented test conditions, (2) establishing the annoyance criteria for impulse noise, (3) defining tower wake characteristics, (4) comparing noise predictions with noise measurements, and (5) comparing noise predictions with annoyance criteria.

NASA-TT-F-15,346, 1974, Technical Translation.

**PROGRESS IN THE UTILIZATION OF WIND POWER**

Meyer, G. W.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 73-74.

**THE USE OF PAPER HONEYCOMB FOR PROTOTYPE BLADE CONSTRUCTION FOR SMALL TO MEDIUM-SIZED WIND DRIVEN GENERATORS**

Meyer, H.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 27-34.

**LARGE HAWT WAKE MEASUREMENT AND ANALYSIS**

Miller, A. H. , Wegley, H. L. , and Buck, J. W.

An overview is presented of the research that has been performed on the modeling of the wake region of a large HAWT, including theory, wind tunnel studies, and field measurements. Studies at the Mod-2 site near Goldendale, Washington, are described in which the turbines are used as an indicator of both momentum deficit and induced turbulence effects in the wake. Only momentum deficits are addressed, with analyses of both turbine power output deficits and wind energy deficits as measured by anemometers on meteorological towers. Some evidence of the influence of certain topographic features on the wakes of widely-separated wind turbines is presented.

PNL-4864 Report, 1984, Pacific Northwest Laboratories (Richland, Washington).

**DEVELOPMENT AND VERIFICATION OF MOD-2 AND MOD-0A SIMULATION MODELS**

Miller, A. H. , and Formica, W. J.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 337-351.

# **LONG-TERM ENERGY CAPTURE AND THE EFFECTS OF OPTIMIZING WIND TURBINE OPERATING STRATEGIES**

Miller, A. H. , and Formica, W. J.

A research effort is described which seeks possible methods of increasing energy capture by wind turbines without affecting the turbine design. Emphasis is on optimizing the wind turbine operating strategy, embodying startup, shutdown, and yawing algorithms. Results are presented of time-dependent simulations of a 2.5-MW Mod-2 wind turbine using various site-dependent operating strategies, indicating that site-specific fine tuning can produce significant increases in long-term energy capture while reducing the number of start-stop cycles and yawing maneuvers.

**86N31983** NASA-TM-88811 DOE/NASA-20320/71, 1986; also Proceedings, Fifth ASME Wind Energy Symposium, SED-Volume 2, 1986, American Society of Mechanical Engineers (New York).

# **SUMMARY OF NASA/DOE AILERON-CONTROL DEVELOPMENT PROGRAM FOR WIND TURBINES**

Miller, D. R.

The development of aileron-control for wind turbines is discussed. Selected wind tunnel test results and full-scale rotor test results are presented for various types of ailerons. Finally, the current status of aileron-control development is discussed. Aileron-control was considered as a method of rotor control for use on wind turbines based on its potential to reduce rotor weight and cost. Following an initial feasibility study, a 20-percent chord aileron-control rotor was fabricated and tested on the NASA/DOE Mod-0 experimental wind turbine. Results from these tests indicated that the 20 percent chord ailerons regulated power and provided overspeed protection, but only over a very limited wind speed range. The next aileron-control rotor to be tested on the Mod-0 had 38-percent chord ailerons and test results showed these ailerons provided overspeed protection and power regulation over the Mod-0's entire operational wind speed range.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 537-545.

# **SUMMARY OF NASA/DOE AILERON-CONTROL DEVELOPMENT PROGRAM FOR WIND TURBINES**

Miller, D. R. , and Sirocky, P. J.

This paper briefly traces the development of aileron controls for wind turbines and presents selected wind tunnel and full-scale turbine rotor test results. The current status of the development of aileron control surfaces for HAWTs is discussed. Tests on the 125-ft diameter Mod-0 experimental HAWT showed that ailerons with widths of 20 percent of chord proved power regulation and overspeed protection only over a very limited range of wind speeds. Increasing aileron width to 38 percent of chord provided satisfactory control over the entire operating range of the Mod-0.

**85A45513** Proceedings, 19th Intersociety Energy Conversion Engineering Conference, Volume 4, 1984, American Nuclear Society (La Grange Park, Illinois), pp. 2369-2373.

# **AILERON CONTROLS FOR WIND TURBINE APPLICATIONS**

Miller, D. R. , and Puthoff, R. L.

Horizontal axis wind turbines which utilize partial or full variable blade pitch to regulate rotor speed were examined. The weight and costs of these systems indicated a need for alternate methods of rotor control. Aileron control is an alternative which has potential to meet this need. Aileron control rotors were tested on the Mod-0 wind turbine to determine their power regulation and shutdown characteristics. Test results for a 20- and 38-percent chord aileron control rotor are presented. Test is shown that aileron control is a viable method for safely controlling rotor speed, following a loss of general load.

**85N30476** NASA-TM-83472 DOE/NASA/20320-50, 1985; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 803-813.

# **ANALYTICAL MODEL FOR PREDICTING EMERGENCY SHUTDOWN OF A TWO-BLADED HORIZONTAL AXIS WIND TURBINE**

Miller, D. R. , and Ensworth, C. B. F. III

An analytical model was developed to predict the shutdown characteristics of a large two bladed horizontal-axis wind turbine following a sudden loss of generator load. The analytical model is described and used to predict rotor speed time histories following a loss of load, for a tip-control rotor and an aileron control rotor. These shutdown predictions are compared with experimental results from full-scale tests conducted on the Mod-0 100 kW wind turbine with both a tip control rotor and an aileron-control rotor. Predicted and measured rotor speed time histories are compared based on peak overspeed rpm, time at which this peak rpm occurs, and the general shape of the time history curve. The results of this comparison

indicated there was good agreement between predictions and the full scale test results, thus verifying the analytical shutdown model. In general, the best agreement between predictions and full-scale test results was obtained up to the time where the peak overspeed rpm occurred.

**85N16299** NASA-TM-86918 DOE/NASA/20320-61, 1984.

#### **SHUTDOWN CHARACTERISTICS OF THE MOD-0 WIND TURBINE WITH AILERON CONTROLS**

Miller, D. R. , and Corrigan, R. D.

Experimental and analytical loss-of-load shutdown characteristics are presented for a HAWT rotor with ailerons that are 20% and 38% of blade chord in width. No-load equilibrium rotor rotational speeds for the two configurations are compared for various aileron deflection angles. Rotor speed time histories measured during loss-of-load shutdowns are compared to analytical predictions, and the ability of ailerons to control rotor overspeed is discussed. Horizontal-axis wind turbines normally utilize partial- or full-span blade pitch to regulate rotor speed and power. The weight and costs of these systems indicated a need for alternate methods of rotor control. Aileron control is an alternative which has the potential to meet this need. The NASA Lewis Research Center has been experimentally testing aileron control rotors on the Mod-0 wind turbine to determine their power regulation and shutdown characteristics. Test results indicated that the 38 percent chord ailerons provided overspeed protection over the entire Mod-0 operational wind speed range, and had a no-load equilibrium tip speed ratio of 1.9. Thus, the 38-percent chord ailerons had much improved aerodynamic braking capability when compared with the first aileron-control rotor having 20-percent chord ailerons.

**85N11458** NASA-TM-86867 DOE/NASA/20320-60, 1984; also Proceedings, 19th Intersociety Energy Conversion Engineering Conference, 1984, American Nuclear Society (La Grange Park, Illinois).

#### **AILERON CONTROLS FOR WIND TURBINE APPLICATIONS**

Miller, D. R. , and Puthoff, R. L.

Horizontal axis wind turbines which utilize partial or full variable blade pitch to regulate rotor speed were examined. The weight and costs of these systems indicated a need for alternate methods of rotor control. Aileron control is an alternative which has potential to meet this need. Aileron control rotors were tested on the Mod-0 wind turbine to determine their power regulation and shutdown characteristics. Test results for a 20% and 38% chord aileron control rotor are presented. Test is shown that aileron control is a viable method for safely controlling rotor speed, following a loss of general load.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), pp. 105-114.

#### **SUMMARY OF 38 PERCENT CHORD AILERON-CONTROL ROTOR TESTS**

Miller, D. R. , and Corrigan, R. D.

This paper presents the results of loss-of-load shutdown and power regulation tests conducted on the Mod-0 experimental HAWT (125-ft diameter) with aileron control surfaces on the two blades. Overspeed following loss of load was limited to less than 20% for winds up to 12 m/s, and mean generator power was regulated effectively. The 38 percent width of these ailerons provided much improvement in braking and power regulation, compared with the 20 percent width tested earlier.

**78N19627** Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 109-116.

#### **SUMMARY OF STATIC LOAD TEST OF THE MOD-0 BLADE**

Miller, D. R.

A static load test was performed on the spare Mod-0 wind turbine blade to define load transfer at the root end of the blade, and to validate stress analysis of this particular type of blade construction (frame and stringer). Analysis of the load transfer from the airfoil skin to the shank tube predicted a step change in spanwise stress in the airfoil skin at station 81.5 inches (STA 81.5). For flatwise bending a 40% reduction in spanwise stress was predicted, and for edgewise bending a 6% reduction. Experimental results verified the 40% reduction for flatwise bending, but indicated about a 30% reduction for edgewise bending.

**78N19616** NASA CP 2034 DOE CONF-771148; 287 pp; pp. 269-274 (Panel Discussion Summaries) and pp. 285-287 (List of Participants).

#### **PROCEEDINGS OF THE WIND TURBINE STRUCTURAL DYNAMICS CONFERENCE**

Miller, D. R. , Editor

A workshop on wind turbine structural dynamics was held at the Lewis Research Center in 1977 to review and document current United States work on the dynamic behavior of large wind turbines, primarily of the horizontal-axis type, and to

identify and discuss other wind turbine configurations that may have lower cost and weight. Twenty-eight presentations provided information on the following topics: (1) Methods for calculating dynamic loads; (2) aeroelasticity stability (3) wind loads, both steady and transient; (4) critical design conditions; (5) drive train dynamics; and (6) behavior of operating wind turbines.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 67-78.

**COMPARATIVE PERFORMANCE TESTS ON THE MOD-2, 2.5 MW WIND TURBINE WITH AND WITHOUT VORTEX GENERATORS**

Miller, G. E.

A test program is described which was conducted on a Mod-2 2.5-MW HAWT near Goldendale, Washington, to systematically study the effect of vortex generators (VGs) on power performance. Results are presented for three test configurations: Without VGs (baseline data), with VGs only on the mid-blade sections, and VGs on both mid-blade and tip sections. Significant performance improvements were found with both VG configurations.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 115-138.

**CALCULATION OF DESIGN LOADS FOR THE MOD-5A 7.3 MW WIND TURBINE SYSTEM**

Mirandy, L. P. , and Strain, J. C.

Design loads are presented for the General Electric Mod-5A HAWT, which consists of a 400-ft diameter, upwind, two-bladed, teetered rotor connected to a 7.3-MW variable-speed generator. Fatigue loads are specified in the form of histograms for the 30-year life of the machine, while limit loads have been derived from transient dynamic analysis at critical operating conditions. Loads prediction was accomplished using state-of-the-art aeroelastic analyses extended by methods which develop statistical distributions. Test vs theory correlations are presented to demonstrate the capabilities of the computer models used. In addition, Mod-5A design loads are compared with those of existing HAWTs.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 240-243.

**NSF PRESENTATION -- SUMMARY OF THE NATIONAL SCIENCE FOUNDATION'S ENERGY CONVERSION PROGRAM**

Morse, F. H.

**74N16763** Proceedings, Wind Energy Conversion Systems Conference, 1973, NSF/RA/W-73-006, pp. 27-32.

**WHERE THERE IS A WIND, THERE IS A WAY**

Mosher, C. A.

A shift in USA energy policy from oil or natural gases to thermonuclear fission and solar energy is predicted. A massive diversified energy research and development effort to productively harness the energy in the winds is outlined to develop commercially feasible wind energy conversion systems - considered a form of solar energy - in the near future.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 136-143.

**LOADS AND FATIGUE EVALUATION OF HAMILTON STANDARD WTS-4 WIND TURBINE**

Murtha-Smith, S.

The methods and results of a load and fatigue life evaluation program conducted on this 4-MW prototype HAWT near Medicine Bow, Wyoming, are described. The task required development of new methodology for evaluating the fatigue lives of key components and identifying the contributors to cumulative damage and these are discussed and illustrated. Techniques used were found to be very effective, and all key components were found to have long fatigue lives.

Proceedings, Wind Energy Expo '84 and National Conference, 1984, American Wind Energy Association (Washington, DC), pp. 37-46.

**REAL-TIME LOAD ANALYSIS FOR THE WESTINGHOUSE WWG-0500 TURBINE BLADE**

Mutone, G. A. , and Andersen, T. S.

The results of dynamic analyses conducted with a hybrid computer wind turbine model are presented, providing an assessment of blade loads and power performance with detailed drive train and control action and response during turbulent winds. This computer model produces time-varying (in real time) blade loads for all radial stations during any postulated transient and enables easy and quick evaluation of turbine drive train and controller dynamic effects. Comparisons to WEST-1 simulator results and experimental data are given.

**90N70729 NASA-TM-101933; 85N73388 NASA-TM-87481; 85N73387 NASA-TM-87482; 78N29583 NASA-TM-79757**  
**THE 200-KILOWATT WIND TURBINE PROJECT**

National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.

This series of publications contains text, figures, and photographs which describe the project objectives, designs, installations, and achievements of the four Mod-0A wind turbines installed at mainland and island utility sites in the U.S. The overall objective of the project is to obtain early operation and performance data while gaining initial experience in the operation of large, horizontal-axis wind turbines in typical utility environments. Several of the key issues addressed include the following: (1) impact of the variable power output (due to varying wind speeds) on the utility grid (2) compatibility with utility requirements (voltage and frequency control of generated power) (3) demonstration of unattended, fail-safe operation (4) reliability of the wind turbine system (5) required maintenance and (6) initial public reaction and acceptance. The Mod-0A wind turbines compose the first of three successive generations of experimental wind power systems developing the required cost-effective technology. Proposed wind turbines of the two following generations, although similar in their two-bladed rotor designs, are larger in both physical size and rated power generation.

**83N71840 NASA-TM-85184 and 83N71839 NASA-TM-85183**

**A COMPILATION OF REPORTS ON TERRESTRIAL ENERGY CONVERSION AND ADVANCED GROUND PROPULSION**

National Aeronautics and Space Administration, Lewis Research Center (Cleveland, Ohio).

**79N17333 NASA-TM-79032 DOE/NASA/1028-79/1, 1979.**

**A 200-KW WIND TURBINE GENERATOR CONCEPTUAL DESIGN STUDY**

National Aeronautics and Space Administration, Lewis Research Center (Cleveland, Ohio).

A conceptual design study was conducted to define a 200 kW wind turbine power system configuration for remote applications. The goal was to attain an energy cost of 1 to 2 cents per kilowatt-hour at a 14-mph site (mean average wind velocity at an altitude of 30 ft.) The costs of the Clayton, New Mexico, Mod-0A (200-kW) were used to identify the components, subsystems, and other factors that were high in cost and thus candidates for cost reduction. Efforts devoted to developing component and subsystem concepts and ideas resulted in a machine concept that is considerably simpler, lighter in weight, and lower in cost than the present Mod-0A wind turbines. In this report are described the various innovations that contributed to the lower cost and lighter weight design as well as the method used to calculate the cost of energy.

**78N76500 NASA-TM-79508**

**PROCEEDINGS OF THE NSF/NASA/UTILITY WIND ENERGY CONFERENCE**

National Aeronautics and Space Administration, Lewis Research Center (Cleveland, Ohio).

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,

NASA CP 2106, DOE CONF-7904111. pp. 173-184.

**TEST RESULTS OF THE DOE/SANDIA 17 METER VAWT**

Nellums, R. O. , and Worstell, M. H.

The DOE/Sandia 17 meter VAWT began collecting operational data in March 1977, with a variety of rotor and drive train configurations. This report contains a brief review of the test program, followed by a presentation of the performance results and their significance, and includes a discussion of operational difficulties occurring over the past two years.

Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. II, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 557-568.

**MEDICINE BOW WIND PROJECT**

Nelson, L. L.

This paper discusses the study results of the Bureau of Reclamation's wind energy project at Medicine Bow, Wyoming, and summarizes the current construction status of the two megawatt-scale wind turbines that will serve as system verification units. The future of wind energy development by the Bureau is discussed. An analysis based on "willingness to pay" was developed, with the conclusion that a 100 MW wind power station at Medicine Bow has economic and financial feasibility.

**74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006,**  
 pp. 33-40.

**NEED FOR A REGIONAL WIND SURVEY**

Nelson, V. , and Gilmore, E.

**84A33766** In Solar Energy, Volume 32, No. 5, 1984, pp. 591-596.

**REVIEW OF THE DOE/NASA WIND TURBINE ENGINEERING INFORMATION SYSTEM**

Neustadter, H. E. , and Spera, D. A.

A statistical analysis of data obtained from the Technology and Engineering Information Systems was made. The systems analyzed consist of the following elements: (1) sensors which measure critical parameters (e.g. , wind speed and direction, output power, blade loads and component vibrations); (2) remote multiplexing units (RMUs) on each wind turbine which frequency-modulate, multiplex and transmit sensor outputs; (3) on-site instrumentation to record, process and display the sensor output; and (4) statistical analysis of data. Two examples of the capabilities of these systems are presented. The first illustrates the standardized format for application of statistical analysis to each directly measured parameter. The second shows the use of a model to estimate the variability of the rotor thrust loading, which is a derived parameter.

**85A36750** Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), pp. 61-67; in Journal of Solar Energy Engineering, Volume 107, 1985, pp. 240-243.

**METHOD FOR EVALUATING WIND TURBINE WAKE EFFECTS ON WIND FARM PERFORMANCE**

Neustadter, H. E. , and Spera, D. A.

A method of testing the performance of a cluster of wind turbine units and data analysis equations are presented which together form a simple and direct procedure for determining the reduction in energy output caused by the wake of an upwind turbine. This method appears to solve the problems presented by data scatter and wind variability. Test data from the three-unit Mod-2 wind turbine cluster at Goldendale, Washington, are analyzed to illustrate the application of the proposed method. In this sample case the reduction in energy was found to be about 10 percent when the Mod-2 units were separated a distance equal to seven diameters and winds were below rated.

**82N23696** Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 113-120.

**APPLICATIONS OF THE DOE/NASA WIND TURBINE ENGINEERING INFORMATION SYSTEM**

Neustadter, H. E. , and Spera, D. A.

A statistical analysis of data obtained from the Technology and Engineering Information Systems was made. The systems analyzed consist of the following elements: (1) sensors which measure critical parameters (e.g. , wind speed and direction, output power, blade loads and component vibrations); (2) remote multiplexing units (RMUs) on each wind turbine which frequency-modulate, multiplex and transmit sensor outputs; (3) on-site instrumentation to record, process and display the sensor output; and (4) statistical analysis of data. Two examples of the capabilities of these systems are presented. The first illustrates the standardized format for application of statistical analysis to each directly measured parameter. The second shows the use of a model to estimate the variability of the rotor thrust loading, which is a derived parameter.

**81N13463** NASA-TM-81603 DOE/NASA/1028-28, 1980; also Proceedings, Detection, Diagnosis and Prognosis Symposium, 1980, National Bureau of Standards (Washington, DC).

**DATA ACQUISITION AND ANALYSIS IN THE DOE/NASA WIND ENERGY PROGRAM**

Neustadter, H. E.

Four categories of data systems, each responding to a distinct information need are presented. The categories are: control, technology, engineering and performance. The focus is on the technology data system which consists of the following elements: sensors which measure critical parameters such as wind speed and direction, output power, blade loads and strains, and tower vibrations; remote multiplexing units (RMU) mounted on each wind turbine which frequency modulate, multiplex and transmit sensor outputs; the instrumentation available to record, process and display these signals; and centralized computer analysis of data. The RMU characteristics and multiplexing techniques are presented. Data processing is illustrated by following a typical signal through instruments such as the analog tape recorder, analog to digital converter, data compressor, digital tape recorder, video (CRT) display, and strip chart recorder.

**80A35730** and **79N26502** NASA-TM-73832 DOE/NASA/1004-79/16, 1979; also Proceedings, Conference and Workshop on Wind Energy Characteristics and Wind Energy Siting, 1979, American Meteorological Society (Boston, Massachusetts), pp. 179-189.

**THE USE OF WIND DATA WITH AN OPERATIONAL WIND TURBINE IN A RESEARCH AND DEVELOPMENT ENVIRONMENT**

Neustadter, H. E.

It is noted that in 1976, 17 candidate sites were identified for detailed evaluation as potential sites for installation of large, horizontal axis wind turbines (WT). Attention is given to the Mod-0A, a 200 kW WT located in Clayton, New Mexico. The discussion covers the meteorological data collected, some of the analyses based on these wind data as well as additional areas

currently being investigated in relation to these data. The status of the use of wind information is presented in four areas, namely: operational control, design verification, power performance analysis, and lifetime estimation. Attention is given to some of the identified wind information needs and the steps taken to meet these needs.

DOE/NASA/1010-77/4, 1977.

**WIND ENERGY UTILIZATION -- A BIBLIOGRAPHY WITH ABSTRACTS, CUMULATIVE VOLUME 1944/1974**  
New Mexico University

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 186-196.

**FRENCH WIND GENERATOR SYSTEMS**

Noel, J. M.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 375-390.

**THE USEFUL POTENTIAL OF USING EXISTING DATA TO UNIQUELY IDENTIFY PREDICTABLE WIND EVENTS AND REGIMES -- PART II**

Notis, C.

This paper describes the strong relationships observed between a particular synoptic type of weather and the wind regime at each of four distinctive sites. Statistics indicate certain patterns which result in strong and weak winds. A preferred wind direction is associated with the strongest wind at each site. Relationships between surface wind speed and 850-mb atmospheric pressure. Results show that wind speeds and directions can be correlated with synoptic weather patterns using existing meteorological data.

**88A10970** Proceedings, Sixth ASME Wind Energy Symposium, SED-Vol. 3, 1987, American Society of Mechanical Engineers (New York), pp. 33-40.

**CHORDWISE PRESSURE MEASUREMENTS ON A BLADE OF MOD-2 WIND TURBINE**

Nyland, T. W.

Pressure measurements covering a range of wind velocities were made at one span location on a blade of the Mod-2 Wind Turbine. The data show the existence of higher pressure coefficients than would be expected from wind tunnel data. These high pressure coefficients may be the result of three-dimensional flow over the blade that delays flow separations. Data is presented showing the repetitiveness and abrupt changes in the pressure distribution that occurs as the blade rotates. Calculated values of suction and flap coefficients are also presented.

**87N26455** NASA-TM-89903 DOE/NASA/20320-72, 1987.

**SURFACE PRESSURE MEASUREMENTS ON THE BLADE OF AN OPERATING MOD-2 WIND TURBINE WITH AND WITHOUT VORTEX GENERATORS**

Nyland, T. W.

Pressure measurements covering a range of wind velocities were made at one span location on a blade of the Mod-2 Wind Turbine. The data show the existence of higher pressure coefficients than would be expected from wind tunnel data. These high pressure coefficients may be the result of three-dimensional flow over the blade that delays flow separations. Data is presented showing the repetitiveness and abrupt changes in the pressure distribution that occurs as the blade rotates. Calculated values of suction and flap coefficients are also presented.

**82N21710** NASA-TM-82711 DOE/NASA/20370-22, 1982.

**MICROPROCESSOR CONTROL SYSTEM FOR 200-KILOWATT MOD-0A WIND TURBINES**

Nyland, T. W. , and Birchenough, A. G.

The microprocessor system and program used to control the operation of the 200-kW Mod-0A wind turbines is described. The system is programmed to begin startup and shutdown sequences automatically and to control yaw motion. Rotor speed and power output are controlled with integral and proportional control of the blade pitch angle. Included in the report are a description of the hardware and a discussion of the software programming technique. A listing of the PL/M software program is given.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 103-106.

**ADVANTAGES OF THE DIFFUSER-AUGMENTED WIND TURBINE**

Oman, R. A. , and Foreman, K. M.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 80-88.

**ROTOR DYNAMIC CONSIDERATIONS FOR LARGE WIND POWER GENERATOR**

Ormiston, R. A.

EPRI-AP-3896, Project 1996-3, 1984, Electric Power Research Institute (Palo Alto, California).

**SOLANO COUNTY MOD-2 WIND TURBINE FIELD EXPERIENCE**

Pacific Gas and Electric Company

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 19-25.

**DOUBLE-MULTIPLE STREAMTUBE MODEL FOR DARRIEUS WIND TURBINES**

Paraschivoiu, I.

This proposed method for calculating the aerodynamic forces on the curved blades of a Darrieus VAWT uses multiple streamtubes divided into two parts: One each for the upwind and downwind half-cycles of the rotor. Variations in induced velocities result in larger forces upwind. Comparisons with previous analytical methods and field test data show two major advantages for the proposed model, namely much shorter computer time than the three-dimensional vortex mode. and more accuracy than the basic multiple-streamtube model. Calculations were made using the CARDAA Code developed at IREQ.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 331-336.

**WIND AND TURBINE CHARACTERISTICS NEEDED FOR INTEGRATION OF WIND TURBINE ARRAYS INTO A UTILITY SYSTEM**

Park, G. L.

Steps used by utility planners are summarized and the type of wind and turbine data needed for integration of wind turbine arrays into an electrical network are suggested.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 103-120.

**THE DANISH LARGE WIND TURBINE PROGRAM**

Pederson, B. M.

A short account is given of the Danish wind energy program and its present status. Results and experiences from tests on the Gedser windmill (200 kW) are presented. The key results are presented from the preliminary design study and detailed design of two new WECS (630 kW each). These two new WECS are planned to go into operation in mid-1979. The Tvind project (2 MW) is briefly mentioned.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 295-301.

**THE EFFECT OF  $\delta_3$  ON A YAWING HAWT BLADE AND ON YAW DYNAMICS**

Perkins, F. W. , and Jones, R.

A single-degree-of-freedom aeroelastic computer model, WMSTAB3, has been employed to perform a parametric analysis of HAWT blade behavior during yaw maneuvers. The effects of  $\delta_3$  angle and flapping stiffness on flapping frequency, phase, and magnitude are discussed, obtained from over 1,000 different combinations of configuration parameters. Moments transmitted to the fixed system during yaw maneuvers are calculated and reduced to time constants of response to step changes in wind direction. The significance of the time constants for the configurations considered relative to yaw response rate and lag angle is discussed, along with their possible significance for large HAWTs.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 323-332.

**KAMAN 40-kW WIND TURBINE GENERATOR -- CONTROL SYSTEM DYNAMICS**

Perley, R.

This HAWT incorporates either an induction or synchronous generator, depending on the application. A combination of feed-forward and feedback control is used to achieve synchronous speed prior to connecting the generator to the load, and

then to control the power level. Rotor parameters that affect the stability of the feedback control loop vary considerably over the wind speed range encountered, so the controller gain was made a function of wind speed. The response speed requirement for the pitch control mechanism is related to the nature of the wind gusts to be encountered, the dynamics of the system, and the acceptable power fluctuations and generator dropout rate. A model is described that allows the probable dropout rate to be determined from a statistical model of wind gusts and the various system parameters.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 552-558.

#### **ANALYSES OF TIP CONTROLLED THREE-BLADED ROTOR FOR MOD-0 TEST BED**

Pintz, A. , Spring, J. W. , and Gallo, C. A.

This paper describes how suitable operating regimes for the Mod-0 experimental HAWT with a 30-m three-bladed rotor were determined on the basis of analytical predictions of rotor performance, blade loads, and drive train dynamics. Computer analyses were performed with the WIND-II and MOSTAB-WT codes (aerodynamic and structural dynamic, respectively) and the Holzer method. Rotor speeds between 20 and 40 rpm are permissible and blade loads for the three-bladed rotor are comparable to those measured with two-bladed rotors. Peak power is 150 percent of the two-bladed power.

NASA-CR-174877 DOE/NASA/0006-1, 1984.

#### **CONCEPTUAL DESIGN OF A FIXED-PITCH WIND TURBINE GENERATOR SYSTEM RATED AT 400 kW**

Pintz, A. , Spring, J. W. , and Kasuba, R.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106 DOE CONF-7904111. pp. 35-59.

#### **THE GENERAL ELECTRIC MOD-1 WIND TURBINE GENERATOR PROGRAM**

Poor, R. H. , and Hobbs, R. B.

The Mod-1 program, to develop the first megawatt class machine in the national wind program, started in September 1976 and has as its objectives the design, fabrication, installation, and test of a megawatt class WTG which generates utility-grade electricity. An overview of the design and installation is given. The blades are the only components remaining to be installed. Recommendations for future designs are given, including a conceptual configuration designated as the Mod-1A with a two-bladed, teetered, uncone upwind rotor.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 177-179.

#### **TECHNICAL FEASIBILITY STUDY FOR THE DEVELOPMENT OF A LARGE CAPACITY WIND POWERED ELECTRICAL GENERATING SYSTEM**

Powe, R. E.

80A28835 and 80N19614 NASA-TM-81444 DOE/NASA/1010-80/6 AIAA Paper A80-28801, 1980; also Proceedings, Wind Energy Conference, 1980, American Institute of Aeronautics and Astronautics, pp. 261-268.

#### **INSTALLATION AND CHECKOUT OF THE DOE/NASA MOD-1 2000-KW WIND TURBINE GENERATOR**

Puthoff, R. L. , Collins, J. L. , and Wolf, R. A.

This paper describes the DOE/NASA Mod-1 wind turbine generator, its assembly and testing, and its installation at Boone, North Carolina. The machine was assembled without the blades, tested, and sent to the site for erection. The blades were transported directly to the site. The paper concludes with performance data taken during the initial tests conducted on the machine. The successful installation and initial operation of the Mod-1 wind turbine generator has had the following results: (1) megawatt-size wind turbines can be operated satisfactorily on utility grids; (2) the structural loads can be predicted by existing codes; (3) assembly of the machine on top of the tower presents no major problem; (4) large blades 100 ft long can be transported long distances and over mountain roads; and (5) operating experience and performance data will contribute substantially to the design of future low-cost wind turbines.

76N21703 NASA-TM-X-3390 ERDA/NASA/1004-77/5, 1976.

#### **FABRICATION AND ASSEMBLY OF THE ERDA/NASA 100 KILOWATT EXPERIMENTAL WIND TURBINE**

Puthoff, R. L.

As part of the Energy Research and Development Administration (ERDA) wind-energy program, NASA Lewis Research Center has designed and built an experimental 100-kW wind turbine. The two-bladed turbine drives a synchronous alternator that generates its maximum output of 100 kW of electrical power in a 29-km/hr (18-mph) wind. The design and assembly

of the wind turbine were performed at Lewis from components that were procured from industry. The machine was installed atop the tower on September 3, 1975.

**75N29546 and 78N76991** NASA-TM-X-71758 ERDA/NASA/1004-77/8, 1975; also Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 21-36.

#### **STATUS OF 100 KW EXPERIMENTAL WIND TURBINE GENERATOR PROJECT**

Puthoff, R. L. , and Sirocky, P. J.

The Energy Research and Development Administration and the NASA Lewis Research Center have engaged jointly in a Wind Energy Program which includes the design and erection of a 100 kW wind turbine generator. This test machine consists of a rotor turbine, transmission, shaft, alternator, and tower. The rotor, measuring 125 feet in diameter and consisting of two variable pitch blades, operates at 40 rpm and generates 100 kW of electrical power at a wind velocity of 189 mph. The entire assembly is placed on top of a tower 100 feet above ground level. The machine is currently in the assembly phase and will be ready for operation in August, 1975.

**74N31527** NASA-TM-X-71585 ERDA/NASA/1004-77/6, 1974; also Proceedings, International Solar Energy Society Conference (Ft. Collins, Colorado), 1974.

#### **PRELIMINARY DESIGN OF A 100 kW TURBINE GENERATOR**

Puthoff, R. L. , and Sirocky, P. J.

The National Science Foundation and the Lewis Research Center have engaged jointly in a Wind Energy Program which includes the design and erection of a 100 kW wind turbine generator. The machine consists primarily of a rotor turbine, transmission, shaft, alternator, and tower. The rotor, measuring 125 feet in diameter and consisting of two variable pitch blades operates at 40 rpm and generates 100 kW of electrical power at 18 mph wind velocity. The entire assembly is placed on top of a tower 100 feet above ground level.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 7-22.

#### **WIND POWER: YESTERDAY, TODAY, AND TOMORROW**

Putnam, P. C.

Palmer C. Putnam, who conceived and led the development of the historic 1,250-kW Smith-Putnam wind turbine in the late 1930's and early '40's (the first megawatt-scale wind power plant in the U.S.), recounts early decisions made regarding machine configuration, design, and siting; presents his views on current wind power developments; and looks ahead to future prospects.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 137-145.

#### **SUPERFLYWHEEL ENERGY STORAGE SYSTEM**

Rabenhorst, D. W.

**79A38888 and 79N30719** NASA-TM-79170 DOE/NASA/1028-79/23 AIAA Paper 79-0965, 1979; also Proceedings, Terrestrial Energy Systems Conference, 1979, American Institute of Aeronautics and Astronautics (Orlando, Florida), 19 pp.

#### **WIND TURBINES FOR ELECTRIC UTILITIES - DEVELOPMENT STATUS AND ECONOMICS**

Ramler, J. R. , and Donovan, R. M.

The technology and economics of the large, horizontal-axis wind turbines currently in the Federal Wind Energy Program are presented. Wind turbine technology advancements made in the last several years are discussed. It is shown that, based on current projections of the costs of these machines when produced in quantity, they should be attractive for utility application. The cost of electricity (COE) produced at the busbar is shown to be a strong function of the mean wind speed at the installation site. The break-even COE as a fuel-saver is discussed and the COE range that would be generally attractive to utilities is indicated.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 185-190.

#### **A CONCEPTUAL FRAMEWORK FOR EVALUATING VARIABLE SPEED GENERATOR OPTIONS FOR WIND APPLICATIONS**

This paper reviews variable speed technology options for wind turbine generators, providing advantages and disadvantages of each. Furthermore, the dynamic properties of variable speed systems are contrasted with synchronous

operation. Finally, control properties of variable speed systems are examined.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 773-731.

#### **A REVIEW OF UTILITY ISSUES FOR THE INTEGRATION OF WIND ELECTRIC GENERATION**

Reddoch, T. W. , and Barnes, P. R.

Utility issues are categorized in three major areas: Planning, operations, and dynamic interaction. Representative studies have been chosen for each area to illustrate problems and to alleviate some concerns. The emphasis of this paper is on individual large wind turbines and arrays of turbines for deployment at the bulk level in a utility system.

**79N28725** NASA-TM-79193 DOE/NASA/20305-79/3, 1979.

#### **SAFETY CONSIDERATIONS IN THE DESIGN AND OPERATION OF LARGE WIND TURBINES**

Reilly, D. H.

The engineering and safety techniques used to assure the reliable and safe operation of large wind turbine generators utilizing the Mod 2 Wind Turbine System Program as an example is described. The techniques involve a careful definition of the wind turbine's natural and operating environments, use of proven structural design criteria and analysis techniques, an evaluation of potential failure modes and hazards, and use of a fail safe and redundant component engineering philosophy. The role of an effective quality assurance program, tailored to specific hardware criticality, and the checkout and validation program developed to assure system integrity are described.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 109-114.

#### **WIND-POWERED ASYNCHRONOUS AC/DC/AC CONVERTER SYSTEM**

Reitan, D. K.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 173-193.

#### **ASSESSING THE REPRESENTATIVENESS OF WIND DATA FOR WIND TURBINE SITE EVALUATION**

Renné, D. S. , and Corotis, R. B.

This paper discusses how assessment of the representativeness of available wind data can be used to develop a more-effective on-site meteorological measurement program. Subjects include the degree to which data represent the interannual variability of diurnal, seasonal, and annual wind statistics; degree to which the data represent actual geographic and topographic conditions at the site; and the degree of impact through modification in the lower atmospheric boundary layer caused by large numbers of turbines. Mathematical models for adjusting available data to local conditions are given, and research on alternative measurement strategies is described.

**79A10235** and **78N26553** NASA-TM-78916 DOE/NASA/1004-78/13, 1978; also Proceedings, 13th Intersociety Energy Conversion Engineering Conference, Volume 3, 1978, Society of Automotive Engineers (Warrendale, Pennsylvania), pp. 2060-2063.

#### **DOE/NASA Mod-0A WIND TURBINE PERFORMANCE**

Richards, T. R. , and Neustadter, H. E.

The NASA Lewis Research Center has designed, built, and is operating a 200-kW wind turbine (designated the Mod-0A-1) at Clayton, New Mexico. This is the first of three identical 200 kW wind turbines to be operated on electric utility networks. This paper compares the measured power-vs-speed performance of the Mod-0A-1 with predictions made using the PROP code. It is found that the actual performance closely matches predictions.

**81N12981** and **80N32858** NASA-TM-81502 DOE/NASA/23139-1, 1980; also Proceedings, Conference on Selected Technology for Business and Industry, pp. 27-41 (see **81N-12978**); American Power Conference, 1980, Illinois Institute of Technology (Chicago, Illinois); Annual Solar Energy Program Review, 1980, Electric Power Research Institute (Palo Alto, California).

#### **LARGE WIND TURBINES: A UTILITY OPTION FOR THE GENERATION OF ELECTRICITY**

Robbins, W. H. , Thomas, R. L. , and Baldwin, D. H.

The economic and technical potential of wind energy in the United States is discussed. Particular attention is given to the status of wind turbine operational experience as well as the environmental posture of the technology. The wind resource is such that wind energy generation has the potential to save 6-7 quads of energy nationally. Thus, the Federal Government

is sponsoring and encouraging the development of cost effective and reliable wind turbines. One element of the Federal Wind Energy Programs, Large Horizontal Axis Wind Turbine Development, is managed by the NASA Lewis Research Center for the Department of Energy. There are several ongoing wind system development projects oriented primarily toward utility application within this program element. In addition, a comprehensive technology program supporting the wind turbine development projects is being conducted. An overview is presented of the NASA activities with emphasis on application of large wind turbines for generation of electricity by utility systems.

Proceedings, National Conference, American Wind Energy Association, Summer 1980 (Washington, DC), pp. 7-12.  
**ENERGY POTENTIAL AND EARLY OPERATIONAL EXPERIENCE FOR LARGE WIND TURBINES**  
 Robbins, W. H. , and Thomas, R. L.

A status report is presented on several on-going wind system development projects at the NASA Lewis Research Center oriented primarily toward utility application, as well as a comprehensive supporting technology program. Wind turbine economic and environmental considerations are also discussed.

Proceedings, National Conference, American Wind Energy Association, Spring 1979 (Washington, DC), pp. 12-20.  
**LARGE HORIZONTAL AXIS WIND TURBINE DEVELOPMENT**  
 Robbins, W. H. , and Thomas, R. L.

A status report on the NASA program to develop large-scale HAWTs for utility power is given, including both the design, construction, and testing of complete systems and supporting research projects.

**79A46527** Proceedings, Workshop on Economic and Operational Requirements and Status of Large Scale Wind Systems, 1979, Altas Corporation (Santa Cruz, California), pp. 50-72.

**LARGE HORIZONTAL AXIS WIND TURBINE DEVELOPMENT**

Robbins, W. H. , and Thomas, R. L.

The paper presents an overview of the NASA activities in large horizontal axis wind turbine development. First generation technology large wind turbines (Mod-0A, Mod-1) have been designed and are in operation at selected utility sites. Second generation machines (Mod-2) are scheduled to begin operations on a utility site in 1980. These machines are estimated to generate electricity at less than 4 cents/kWh when manufactured in modest production rates. Meanwhile, plans are being made to continue developing wind turbines which can meet the cost goals of 2 to 3 cents/kWh.

**79N26504** NASA-TM-79174 DOE/NASA/1059-79/2, 1979; also Proceedings, Wind Energy Innovative Systems Conference, 1979, National Renewable Energy Laboratory (Golden, Colorado).

**LARGE HORIZONTAL AXIS WIND TURBINE DEVELOPMENT**

Robbins, W. H. , and Thomas, R. L.

An overview of the NASA activities concerning ongoing wind systems oriented toward utility application is presented. First-generation-technology large wind turbines were designed and are in operation at selected utility sites. In order to make a significant energy impact, costs of 2 to 3 cents per kilowatt hour must be achieved. The federal program continues to fund the development by industry of wind turbines which can meet the cost goals of 2 to 3 cents per kilowatt hour. Lower costs are achieved through the incorporation of new technology and innovative system design to reduce weight and increase energy capture.

COO-0092-77/2, 1977, Battelle Memorial Institute (Columbus, Ohio).  
**ENVIRONMENTAL STUDIES RELATED TO THE OPERATION OF WIND ENERGY CONVERSION SYSTEMS**  
 Rogers, S. E.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 375-390.  
**ENVIRONMENTAL EFFECTS OF WIND ENERGY CONVERSION SYSTEMS?**  
 Rogers, S. E.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 593-607.  
**OPERATIONAL EXPERIENCE ON THE MP-200 SERIES COMMERCIAL WIND TURBINE GENERATORS**  
 Rose, M. B.

To date, WTG Energy Systems has installed three medium-scale wind turbine generators with a fourth scheduled to go

on line by January 1982. Turbines are located on Cuttyhunk Island, Massachusetts; Wreck Cove, Nova Scotia; and Whiskey Run, Oregon. The MP-200 system consists of an 80-ft diameter, 3-bladed upwind rotor with steel blade spars atop an 80-ft truss tower, turning at 30 rpm and driving a 350 kVA alternator at 1200 rpm. Tip flaps control the aerodynamic torque of the rotor. Experience gained during thousands of hours of operation is described

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 575-591; and Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 193-206.

#### **DESCRIPTION OF THE 3 MW SWT-3 WIND TURBINE AT SAN GORGONIO PASS CALIFORNIA**

Rybak, S. C.

The SWT-3 wind turbine is a microprocessor-controlled, variable-speed machine with a 169-ft diameter three-bladed, upwind rotor and a 3 MW rating, that is presently operational and undergoing system testing at Southern California Edison's Devers Substation north of Palm Springs, California. The tower, a rigid triangular truss configuration, is rotated about its vertical axis to position the wind turbine into the wind. The blades rotate at variable speed in order to maintain an optimum 6:1 tip speed ratio, using a hydrostatic transmission consisting of fourteen fixed-displacement pumps in the nacelle operating in conjunction with eighteen variable-displacement motors on the ground. Full-blade pitch with on-off hydraulic actuation is used to maintain 3 MW of output power at wind speeds above 40 mph.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 559-564.

#### **WIND TURBINE FLOW VISUALIZATION STUDIES**

Savino, J. M. , and Nyland, T. W.

Flow visualization studies are described which were conducted on the 100-kW 125-ft diameter Mod-0 experimental HAWT, in the neighborhood of the rotor (particularly downwind) and on the suction surfaces of the blades. Techniques are discussed, including the use of smoke grenades, small flow indicators attached to the blades, movies, and still photographs. In low winds sizable flow stream expansion was observed. Blade tip and root vortices dissipated within two rotor diameters downwind. Spanwise flow occurred on blade surfaces in separated flow regions.

85N34444 NASA-TM-87018 DOE/NASA/20320-65, 1985.

#### **REFLECTION PLANE TESTS OF A WIND TURBINE BLADE TIP SECTION WITH AILERONS**

Savino, J. M. , Nyland, T. W. , Birchenough, A. G. , Jordan, F. L. Jr. , and Campbell, N. K.

Tests were conducted in the NASA Langley 30 by 60 foot Wind Tunnel on a full-scale 24-ft long tip section of a 62.5-ft wind turbine blade. The blade tip section was built with ailerons on the trailing edge. The ailerons, which spanned a length of 20 ft, were designed so that two types could be evaluated: plain and balanced. The ailerons were hinged on the suction surface at the 0.62% chord station from the leading edge. The purpose of the tests was to measure the aerodynamic characteristics of the blade section for angles of attack from 0 deg to 90 deg, aileron deflections from +2 deg to -90 deg, and Reynolds numbers of 0.8 and 1.5 million. These data were then used to determine which aileron configuration had the most desirable rotor control and aerodynamic braking characteristics. Tests were also run to determine the effects on the lift, drag, and chordwise force coefficients of vortex generators, leading edge roughness, and gaps between aileron sections and between the ailerons and the blade.

NASA-TM-79202 DOE/NASA/20370-79/17, 1979.

#### **SOME TECHNIQUES FOR REDUCING THE TOWER SHADOW OF THE DOE/NASA MOD-0 WIND TURBINE TOWER**

Savino, J. M. , Burley, R. R. , Wagner, L. H. , and Diedrich, J. H.

78N77012 Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 197-201.

#### **INTRODUCTION TO WIND ENERGY CONVERSION SYSTEMS TECHNOLOGY**

Savino, J. M.

One of the first and most important tasks to be undertaken is that of identifying the most cost-effective WECS configuration for generating ac electrical power for supplying a utility network. This task is being addressed in the ERDA/NASA program by two design studies which were started in November 1974 by the Kaman Aerospace Corporation and the General Electric Company. The results thus far suggest that the most promising WECS configuration with the greatest potential for low cost appears to be one that has a two-bladed constant rpm rotor, a commercial step-up gear-type

transmission, an ac synchronous or induction generator, and either a steel truss type or concrete tower.

**78N23558** NASA-TM-78853 DOE/NASA/1028-78/17, 1978.

**WAKE CHARACTERISTICS OF A TOWER FOR THE DOE-NASA MOD-1 WIND TURBINE**

Savino, J. M. , Wagner, L. H. , and Nash, M.

A 1/40th scale model of a tower concept designed for a Mod-1 wind power turbine was tested in a low speed wind tunnel. Wake wind speed profiles were measured, and from these were determined local values of wake minimum velocity ratio, average velocity ratio, and width over a range of tower elevations and wind approach angles. Comparison with results from two other all tubular models (MOD-0 and eight leg designs) tested earlier in the same tunnel indicated that wake width and flow blockage at the rotor plane of rotation were slightly larger for the MOD-1 tower than for the other two models. The differences in wake characteristics were attributed to differences in tower geometry and member dimensions.

NASA-TM-73868 DOE/NASA/1028-77/14, 1977.

**WAKE CHARACTERISTICS OF AN EIGHT-LEG TOWER FOR A MOD-0 WIND TURBINE**

Savino, J. M. , Sinclair, D. M. , and Wagner, L. H.

**77N13534** NASA-TM-X-73548, 1976.

**WIND TUNNEL MEASUREMENTS OF THE TOWER SHADOW ON MODELS OF THE ERDA/NASA 100-kW WIND TURBINE TOWER**

Savino, J. M. , and Wagner, L. H.

Detailed wind speed profile measurements were made in the wake of 1/25 scale and 1/48 scale tower models to determine the magnitude of the speed reduction (the tower shadow). The 1/25 scale tower modeled closely the actual wind turbine including the service stairway and the equipment elevator rails on one face. The 1/48 scale model was made of all tubular members. Measurements were made on the 1/25 scale model with and without the stairway and elevator rails, and on the 1/48 all tube model without stairs and rails. The test results show that the stairs and rails were a major source of wind flow blockage. The all tubular 1/48 scale tower was found to offer less resistance to the wind than the 1/25 scale model that contained a large number of square sections. Shadow photos are included to show the extent of the blockage offered to the wind from various directions.

**74N34540** NASA-TM-X-71605 ERDA/NASA/1004/77/7, 1974; also Proceedings, Workshop on Advanced Wind Energy Systems, Volume 1, 1974, National Swedish Board for Technical Development and Swedish State Power Board (Stockholm), pp. 1-35 to 1-50.

**A BRIEF SUMMARY OF THE ATTEMPTS TO DEVELOP LARGE WIND-ELECTRIC GENERATING SYSTEMS IN THE U.S.**

Savino, J. M.

Interest in developing large wind-electric generating systems in the United States was simulated primarily by one man, Palmer C. Putnam. He was responsible for the construction of the 1,250 kilowatt Smith-Putnam wind-electric plant. The existence of this system prompted the U. S. Federal Power Commission to investigate the potential of using the winds as a source energy. Also, in 1933 prior to Putnam's effort, there was an abortive attempt by J. D. Madaras to develop a wind system based on the Magnus effect. These three projects comprise the only serious efforts in America to develop large wind driven plants. In this paper the history of each project is briefly described. Also discussed are some of the reasons why wind energy was not seriously considered as a major source of energy for the U. S.

**74N16757** NASA-TM-X-69786 NSF/RA/W-73-006; 258 pp.; Technical Committee Reports, pp. 209-239.

**PROCEEDINGS OF THE 1973 WIND ENERGY CONVERSION SYSTEMS WORKSHOP**

Savino, J. M. , Editor

The National Science Foundation (NSF) and NASA, both deeply interested in the wind as a possible source of non-polluting and inexhaustible energy, decided in March 1973 to hold a workshop in June as a first step in following up the recent work of the NSF/NASA Solar Energy Panel. The purpose of this workshop was to bring together for the first time in more than a decade all those persons actively interested in wind power and as many of the pioneers in the field as could be found to try to (1) determine what was the state of the art of wind energy systems technology and (2) what direction future efforts should take. A total of 83 participants attended this three-day workshop and 47 presentations and panel discussions were heard. Workshop participants believed that the cost of developing wind-driven power systems should be quite low compared to the costs of developing nuclear and other advanced power systems, and that what was needed was a concerted and systematic attack on the economic and technical capabilities of wind energy systems. It is the intent of the NSF/NASA

five-year wind energy program to provide such a needed effort. Conference participants convened in separate groups to discuss, assess the state of the art of their area of specialty, and draw conclusions as to the direction of future work. Summary reports, together with questions and answers and a panel discussion, are presented on the following subjects: Wind characteristics and siting, rotor characteristics, energy storage and energy conversion systems, and applications. A list of attenders is included.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 757-771.

#### **INITIAL UTILITY EXPERIENCE WITH CLUSTER OF THREE MOD-2 WIND TURBINE SYSTEMS**

Seely, D. B. , Warchol, E. J. , Butler, N. G. , and Ciranny, S.

This paper describes the experiences of the Bonneville Power Administration in operating the 7.5-MW cluster of three Mod-2 HAWTs near Goldendale, Washington. Electrical quantities of bus voltage, phase currents, and power are recorded to evaluate any impacts on customers on the 69-kV sub-transmission line, and effects have been essentially undetectable to date. Potential TV sign interference at an existing TV remote pickup and relay station at the cluster site have been avoided by replacing the remote pickups with microwave repeater links for the four TV channels received from Portland, Oregon. Preliminary measurements of noise from the upwind Mod-2 rotors show no pulsing sound problems like those experienced near the Mod-1 HAWT with its downwind rotor. Preliminary assessments are made in regard to adequacy of emergency shutdown systems.

Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. II, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 463-478.

#### **INTERFACING THE MOD-2 COMPLEX WITH THE BONNEVILLE POWER ADMINISTRATION'S TRANSMISSION SYSTEM**

Seely, D. B. , Warchol, E. J. , Butler, N. G. , and Mittelstadt, W. A.

The cluster of three 2.5-MW Mod-2 HAWTs installed and placed into service at Goodnoe Hills in the Federal Columbia River Power System is the first multi-unit wind turbine generator installation which as operated with all generators simultaneously supplying power to a utility electrical system. A chronology of events is given, including incidents, TV measurements, and noise surveys, plus utility charts showing voltage histories during interfacing operations.

Chapter 9 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

#### **ELECTROMAGNETIC INTERFERENCE FROM WIND TURBINES**

Sengupta, D. L. , and Senior, T. B. A.

The current state of understanding of the potential EMI effects of operating wind turbines on various communication systems is summarized, and the analysis and measurement of these effects if described for specific cases. Topics which are discussed include EMI mechanisms, mathematical models for predicting EMI effects, and the results of laboratory and full-scale field measurements.

SERI/STR-211-2086, 1983, National Renewable Energy Laboratory (Golden, Colorado).

#### **TELEVISION INTERFERENCE MEASUREMENTS NEAR THE MOD-2 WT ARRAY AT GOODNOE HILLS, WASHINGTON**

Sengupta, D. L. , Senior, T. B. A. , and Ferris, J. E.

SERI/STR-215-1880 018291-2-T, 1983 and 1981, National Renewable Energy Laboratory (Golden, Colorado).

#### **MEASUREMENTS OF TELEVISION INTERFERENCE CAUSED BY A VERTICAL AXIS WIND MACHINE**

Sengupta, D. L. , Senior, T. B. A. , and Ferris, J. E.

018291-1-T, 1981, University of Michigan (Ann Arbor, Michigan).

#### **MEASUREMENTS OF INTERFERENCE TO TELEVISION RECEPTION CAUSED BY THE MOD-1 WIND TURBINE AT BOONE, NC**

Sengupta, D. L. , Senior, T. B. A. , and Ferris, J. E.

Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. III, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 151-162.

**MEASUREMENTS OF TELEVISION INTERFERENCE PRODUCED BY LARGE HORIZONTAL AXIS WIND TURBINES**

Sengupta, D. L. , and Senior, T. B. A.

On-site measurements of television interference in the vicinity of large-scale wind turbines are described in which some or all of the following data are collected: (1) Ambient signal strength with wind turbine stationary; (2) horizontal plane response of the receiving antenna vs pointing angle, with and without turbine operation; (3) received signal vs time, with turbine operating and antenna pointed at the transmitter and at the turbine; and (4) under the conditions of (3) the received picture is monitored for any video distortion which is recorded. The necessary experimental setup, measurement techniques, and reduction of data to quantitatively estimate interference are described. Typical results obtained in the vicinity of the 2.0-MW Mod-1 HAWT near Boone, North Carolina, are discussed.

014438-3-T, 1980, University of Michigan (Ann Arbor, Michigan).

**TELEVISION INTERFERENCE TESTS ON BLOCK ISLAND, RI**

Sengupta, D. L. , and Senior, T. B. A.

COO-2846-1, 1978, University of Michigan (Ann Arbor, Michigan).

**WIND TURBINE GENERATOR SITING AND TV RECEPTION HANDBOOK -- TECHNICAL REPORT NO. 1**

Sengupta, D. L. , and Senior, T. B. A.

014438-4-F, 1980, University of Michigan (Ann Arbor, Michigan).

**WIND TURBINE INTERFERENCE TO TELEVISION RECEPTION**

Sengupta, D. L. , and Senior, T. B. A.

014438-3-F, 1979, University of Michigan (Ann Arbor, Michigan).

**WIND TURBINE GENERATOR INTERFERENCE TO ELECTROMAGNETIC SYSTEMS**

Sengupta, D. L. , and Senior, T. B. A.

COO/2846-2 014438-2-F, 1978, University of Michigan (Ann Arbor, Michigan).

**ELECTROMAGNETIC INTERFERENCE BY WIND TURBINE GENERATORS -- FINAL REPORT NO. 2**

Sengupta, D. L. , and Senior, T. B. A.

SERI/STR-215-1880 014438-4-T, 1983 and 1979, National Renewable Energy Laboratory (Golden, Colorado).

**LARGE WIND TURBINE SITING HANDBOOK -- TELEVISION INTERFERENCE ASSESSMENT**

Senior, T. B. A. , and Sengupta, D. L.

014438-2-T, 1979, University of Michigan (Ann Arbor, Michigan).

**WIND TURBINE GENERATOR SITING AND TV RECEPTION HANDBOOK -- TECHNICAL REPORT NO. 2**

Senior, T. B. A. , and Sengupta, D. L.

DOE/TIC-11348 014438-1-F, 1977, University of Michigan (Ann Arbor, Michigan).

**TV AND FM INTERFERENCE BY WINDMILLS**

Senior, T. B. A. , Sengupta, D. L. , and Ferris, J. E.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 355-362.

**STATUS OF THE SOUTHERN CALIFORNIA EDISON COMPANY 3 MW WIND TURBINE GENERATOR (WTG) DEMONSTRATION PROJECT**

Scheffler, R. L.

SCE initiated a program to construct and test a 3 MW Schachle Wind Turbine Generator to demonstrate the concept of utility-scale electricity production from a high wind energy resource. Unique features of the Schachle turbine include a three-legged steel pipe tower rotating on a concrete and steel base to keep the 165-ft diameter, three-bladed upwind rotor facing into the wind; laminated wood and fiberglass blades with custom airfoils; and a hydraulic pump-motor link between the rotor and the ground-level generator, rated at 3 MW. This hydraulic link was chosen to allow a less-complex gearbox design and

permit the rotor blades to rotate at speeds varying in proportion the wind speed, for increased aerodynamic efficiency. The background and current status of this project are presented along with a summary of planned future program activities.

NASA-SP-455, 1982.

#### **CAPTURING ENERGY FROM THE WIND**

Schefter, J. L.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 129-138.

#### **PERFORMANCE TESTING OF A 50 KW VAWT IN A BUILT-UP ENVIRONMENT**

Schienbein, L. A.

Results are presented of performance tests carried out on a DAF Indal 50 kW VAWT at a site near Toronto, Canada, under less than satisfactory conditions. The site did not exhibit either unobstructed exposure to winds or strong and steady winds. In addition, the time available for testing was limited. Close agreement between measured and predicted energy outputs was not attained, and a discussion is presented of contributing factors.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 343-352.

#### **EFFECT OF WIND TURBINE GENERATOR MODEL AND SITING ON WIND POWER CHANGES OUT OF LARGE WECS ARRAYS**

Schlueter, R. A. , Park, G. L. , Lotfalian, M. , Dorsey, J. , and Shayanfar, H.

This paper discusses methods of reducing the changes in array power output through selection of the wind turbine model for each site, selection of an appropriate siting configuration, and wind array controls. An analysis is presented of power output changes from an echelon array and a wind farm during the passage of a thunderstorm. Reduction of the array power change over a ten-minute period is shown to reduce the increase in spinning reserve, unloadable generation, and load-following requirements on unit commitment when significant WECS generation is present and the farm penetration constraint is satisfied. Controls on the blade pitch angle of each wind turbine or a battery control are both shown to be beneficial.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 171-176.

#### **EVALUATING VARIABLE SPEED GENERATING SYSTEMS ON THE DOE/NASA MOD-0 WIND TURBINE**

Schmidt, W. C. , and Birchenough, A. G.

Preliminary results from tests of a variable-speed constant-frequency generator system are described, which were conducted on NASA's 100-kW experimental HAWT near Sandusky, Ohio. Tests were run under a variety of operating conditions, including various speeds, power levels, and ramp and step changes. Results are compared to those for a 5%-slip induction generator operating under comparable conditions. Topics discussed include generator system description (wound rotor and cycloconverter), test facility, transient suppression, line current harmonics, and future testing of other VSCF systems.

**74N16784** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA-TM-X-69786, NSF/RA/W-73-006, pp. 146-151.

#### **BATTERIES FOR STORAGE OF WIND-GENERATED ENERGY**

Schwartz, H. J.

Cost effectiveness characteristics of conventional-, metal gas-, and high energy alkali metal-batteries for wind generated energy storage are considered. A lead-acid battery with a power density of 20 to 30 watt/hours per pound is good for about 1,500 charge-discharge cycles at a cost of about \$80 per kilowatt hour. A zinc-chlorine battery that stores chlorine as solid chlorine hydrate at temperatures below 10 C eliminates the need to handle gaseous chlorine; its raw material cost are low and inexpensive carbon can be used for the chlorine electrode. This system has the best chance to replace lead-acid. Exotic alkali metal batteries are deemed too costly at the present stage of development.

NASA-TM-77779, 1985.

#### **DEVELOPMENT OF LARGE WIND ENERGY POWER GENERATION SYSTEM**

Scitran Corporation

**83A44673** Paper, Summer Meeting, 1983, Institute of Electrical and Electronics Engineers, 5 pp.

#### **WIND TURBINE GENERATOR INTERACTION WITH DIESEL GENERATORS ON AN ISOLATED POWER SYSTEM**

Scott, G. W. , Wilreker, V. F. , and Shaltens, R. K.

The results of a dynamic interaction investigation to characterize any disturbances caused by interfacing the Mod 0A wind turbine (150 kW configuration) with the Block Island utility diesel generator grid are reported. The tests were run when only two diesel generators were on line, and attention was given to power, frequency, and voltage time profiles. The interconnected system was examined in the start-up and synchronization phase, normal shutdown and cut-out of the wind turbine, during fixed pitch generation, and during variable pitch operation. Governors were installed on the diesel generators to accommodate the presence of wind-derived electricity. The blade pitch control was set to maintain power at 150 kW or below. Power and voltage transients were insignificant during start-up and shutdown, and frequency aberrations were within the range caused by load fluctuations. It is concluded that wind turbine generation can be successfully implemented by an isolated utility, even with a significant penetration to the total grid output.

**82N16478** NASA-TM-82751 DOE/NASA/20320-34, 1981.  
**VARIABLE GAIN FOR A WIND TURBINE PITCH CONTROL**  
 Seidel, R. C. , and Birchenough, A. G.

The gain variation is made in the software logic of the pitch angle controller. The gain level is changed depending upon the level of power error. The control uses low gain for low pitch activity the majority of the time. If the power exceeds ten percent offset above rated, the gain is increased to a higher gain to more effectively limit power. A variable gain control functioned well in tests on the Mod-0 wind turbine.

**81N29528** NASA-TM-82653 DOE/NASA/20320-32, 1981.  
**TESTS OF AN OVERRUNNING CLUTCH IN A WIND TURBINE**  
 Seidel, R. C. , and Pfanner, H. G.

An overrunning clutch that slipped freely under reverse torque was tested in the drive train of the Mod-0 wind turbine. In low variable wind conditions, the clutch engaged and disengaged smoothly without perturbation or oscillations. The clutch permitted the generator to be connected to the line using a relay instead of an automatic synchronizer. The alternator was connected to the line when the rpm reached 95% of synchronous speed and it motored to synchronous speed in about 0.15 seconds with a momentary power spike of 50 kW. The performance of the clutch was the same with and without the fluid coupling. The ideal power with the clutch was 5 to 7 kW compared to up to 50 kW without the clutch. The overrunning clutch merits consideration in future wind turbine designs as a means of simplifying the control system, increasing energy capture, and increasing the life of blades and electrical switch gear.

**79N16355** NASA-TM-78997 DOE/NASA/1028-78/19, 1978.  
**POWER TRAIN ANALYSIS FOR THE DOE/NASA 100-KW WIND TURBINE GENERATOR**  
 Seidel, R. C. , Gold, H. , and Wenzel, L. M.

Progress in explaining variations of power experienced in the on-line operation of a 100 kW experimental wind turbine-generator is reported. Data are presented that show the oscillations tend to be characteristic of a wind-driven synchronous generator because of low torsional damping in the power train, resonances of its large structure, and excitation by unsteady and nonuniform wind flow. The report includes dynamic analysis of the drive-train torsion, the generator, passive driveline damping, and active pitch control as well as correlation with experimental recordings. The analysis assumes one machine on an infinite bus with constant generator-field excitation.

**78N19629** Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 151-156.  
**POWER OSCILLATION OF THE MOD-0 WIND TURBINE**  
 Seidel, R. C.

The Mod-0 power has noise components with varying frequency patterns. Magnitudes reach more than forty percent power at the frequency of twice per rotor revolution. Analysis of a simple torsional model of the power train predicts less than half the observed magnitude and does not explain the shifting frequencies of the noise patterns.

**85N30479** NASA-TM-83517 DOE/NASA/20320-55, 1983; also Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 145-159.  
**OPERATIONAL RESULTS FOR THE EXPERIMENTAL DOE/NASA MOD-0A WIND TURBINE PROJECT**  
 Shaltens, R. K. , and Birchenough, A. G.

The Mod-0A wind turbine project which was to gain early experience in the operation of large wind turbines in a utility environment is discussed. The Mod-0A wind turbines were a first generation design, and even though not cost effective, the operating experience and performance characteristics had a significant effect on the design and development of the second

and third generation machines. The Mod-0A machines were modified as a result of the operational experience, particularly the blade development and control system strategy. The results of study to investigate the interaction of a Mod-0A wind turbine with an isolated diesel generation system are discussed. The machine configuration, its advantages and disadvantages and the machine performance and availability are discussed.

NASA-TT-F-15,149, 1974, Technical Translation.

#### **RUSSIAN ARTICLES ON WIND-POWERED MACHINES**

Shefter, Y. I.

NASA-CR-4337 DOE/NASA/5266-2, 1990; also Chapter 1 in Wind Turbine Technology, D. A. Spera, Editor, pp. 1-46.

#### **HISTORICAL DEVELOPMENT OF THE WINDMILL**

Shepherd, D. G.

From ancient times to the Smith-Putnam wind turbine project in the 1940's, a technical discussion is presented of the origins of windmills, their mechanical design, and some problems that were solved by early engineers and some that were not. The presentation is aimed at engineers and technically-minded readers.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 299-304.

#### **ENVIRONMENTAL NOISE CONSIDERATIONS FOR THE SITING AND OPERATION OF WIND ENERGY FARMS**

Shepherd, K. P. , and Hubbard, H. H.

The basic phenomena of noise generation, noise propagation, and the effects of noise are reviewed for wind turbine generators in single machine and multiple machine configurations. The roles of individual machine noise spectra and directivity patterns are discussed along with pertinent frequency-weighted noise metrics. Special attention is given to the effects of the wind on noise propagation. Results of sensitivity studies are described to indicate the impact of machine sized and geometric arrangements. Example noise contour calculations are presented for several array geometries.

Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. III, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 163-174.

#### **DEVELOPMENT OF WIND TURBINE NOISE CRITERIA**

Shepherd, K. P. , Grosveld, F. W. , and Stephens, D. G.

A program is described that is developing noise standards for wind turbine generators which will minimize annoyance and which can be used in design specifications. The approach consists of presenting recorded wind turbine noise as stimuli to test subjects in a laboratory listening chamber; varying the stimuli to encompass the designs, operating conditions, and ambient noise levels of current and future installations; and recording responses of the subjects. Results to date have established the threshold of detectability for impulsive noise associated with blade/tower wake interactions and for broadband noise associated with blade boundary layer/trailing edge interactions. The status of the ongoing psychoacoustic tests and the approach to the development of acoustic criteria and standards are described.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 75-79.

#### **THE SAIL WING WINDMILL AND ITS ADAPTATION FOR USE IN RURAL INDIA**

Sherman, M. M.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 427-445.

#### **POTENTIAL ERRORS IN USING ONE ANEMOMETER TO CHARACTERIZE THE WIND POWER OVER AN ENTIRE ROTOR DISK**

Simon, R. L.

Detailed results are presented of a study in which wind data collected at four levels on a 90-m tower in a prospective wind power station area are used to evaluate how well the 10-m wind speed data (with and without intermittent vertical profile measurements) compare with the 90-m tower data. Five different strategies were evaluated and errors estimated for each.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 419-423.

### **NOISE GENERATION OF UPWIND ROTOR WIND TURBINE GENERATORS**

Spencer, R. H.

Noise sources of wind turbines with rotors upstream of the support structure are discussed along with methodology for sound level prediction. Estimated noise levels are presented for a Mod-2 wind turbine operating in both the upwind and downwind configurations. Results indicate that upwind rotor configurations may be advantageous from an acoustical standpoint.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 17 - 26.

### **A MODEL OF ROTATIONALLY-SAMPLED WIND TURBULENCE FOR PREDICTING FATIGUE LOADS IN WIND TURBINES**

Spera, D. A.

Empirical equations are presented with which to model rotationally-sampled (R-S) turbulence for input into structural-dynamic computer codes and calculate wind turbine fatigue loads. These equations are derived from R-S turbulence data which were measured at the vertical-plane array in Clayton, New Mexico. For validation, the equations are applied to the calculation of cyclic flapwise blade loads for the NASA/DOE Mod-2 2.5-MW HAWTs, and the results are compared to measured cyclic loads. Good correlation is achieved, indicating that the R-S turbulence model developed in this study contains the characteristics of the wind which produce many of the fatigue loads sustained by wind turbines. Empirical factors are included which permit the prediction of load levels at specified percentiles of occurrence, which is required for the generation of fatigue load spectra and the prediction of the fatigue lifetimes of structural components.

ASME Press, 1994, American Society of Mechanical Engineers (New York), 638 pp.

### **WIND TURBINE TECHNOLOGY**

Spera, D. A., Editor

This book presents fundamental concepts of wind turbine engineering and is an authoritative guide to state-of-the-art wind turbine engineering. Using detailed case study analyses and applications-oriented advice, expert authors present practical lessons learned from the design and testing of wind turbines of all sizes. Through numerous graphics and numerical examples, the reader is presented with mathematical models developed from basic principles. Leaders in the fields of aerodynamics, structural dynamics and fatigue, meteorology, acoustics and electromagnetic emissions, commercial wind power applications, and utility power systems have contributed to this book. Discussions of economic and environmental considerations and the integration of wind power plants into electric utility systems are included. References and bibliographies guide the reader to additional information in the literature. Common terminology, nomenclature, and graphic styles unify the book chapters, as well as significant amounts of cross-referencing. Appendices contain detailed information such as general references on modern wind turbines, bibliography of wind energy conference proceedings, drawings and data on wind turbines in commercial service in the U.S. and television channel frequencies.

Chapter 2 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

### **INTRODUCTION TO MODERN WIND TURBINES**

Spera, D. A.

The configurations of modern horizontal- and vertical-axis wind turbines are described, and definitions of common wind turbine nomenclature terms are given. Parameters which wind turbine engineers use to analyze power and energy output are introduced with equations and numerical examples. Diagrams of typical power trains, and towers are shown, using current commercial turbines of different sizes as examples.

Chapter 12 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

### **FATIGUE DESIGN OF WIND TURBINES**

Spera, D. A.

Descriptions are presented of the types of fatigue loads common to wind turbines, typical statistical distributions of fatigue loads, empirical equations for estimating fatigue loads during preliminary design, and typical fatigue design procedures.

Proceedings, Wind Energy 1994 Symposium, 1994, American Society of Mechanical Engineers (New York), pp. 253-260.

### **DYNAMIC LOADS IN HORIZONTAL-AXIS WIND TURBINES, PART III: DESIGN TREND CHARTS**

Spera, D. A.

The third and final part of a study is presented that synthesizes NASA/DOE experience with measuring, correlating, and

85N30361 NASA-TM-83470 DOE/NASA/20320-49

**STRUCTURAL ANALYSIS AND COST ESTIMATE OF AN EIGHT-LEG SPACE FRAME AS A SUPPORT STRUCTURE FOR HORIZONTAL AXIS WIND TURBINES**

Sizemore, R. L. , Winemiller, J. R. , Yee, S. T. , and Frederick, G. R.

A structural analysis was performed and a cost estimate was prepared to determine if an eight-leg space frame tower in which the legs lie on the surface of a hyperboloid of revolution was a suitable alternative to the truss-type tower for application to an intermediate size horizontal axis wind turbine. This tower concept had eight straight pipe elements as its main structural members that lie on the surface of a hyperboloid of revolution. The structural analysis included: response to static loads, determination of vibration characteristics, and investigation of overall frame stability. The design was lighter than the four-leg truss-type tower used for the Mod-O and Mod-0A wind turbines. The estimated cost for fabrication and erection of the hyperboloid tower is less than that for any of the four Mod-0A towers constructed to date. It is concluded that the hyperboloid tower concept is a suitable alternative to the truss-type tower for application to horizontal axis wind turbines.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 3-6.

**VIEWPOINT IN RETROSPECT**

Smith, B. E.

President Emeritus of S. Morgan Smith Company, York, Pennsylvania, discusses why his firm undertook the development of the first megawatt-scale wind turbine in the U.S. , the historic Smith-Putnam wind turbine, in the middle of the Great Depression and some of the benefits derived from this project.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 5-7.

**SMITH-PUTNAM WIND TURBINE EXPERIMENT**

Smith, B. E.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 363-373.

**DYNAMICS OF WAKES DOWNSTREAM OF WIND TURBINE TOWERS**

Snyder, M. H. , and Wentz, W. H. Jr.

Near-field wakes downstream of circular cylinders and of 12-sided cylinders were surveyed in a wind tunnel. Local velocity and velocity deficit diagrams are presented. The variation of turbulence in the wake was surveyed and the frequency of the periodic component of wake motion was determined. Differences between wakes of circular cylinders and of 12-sided cylinders are discussed. Also effects of strakes, orientation of the 12-sided cylinders, and rounding of the corners are noted.

WER-15, 1982, Wichita State University (Wichita, Kansas).

**WIND-II USERS MANUAL**

Snyder, M. H.

WER-12, 1981, Wichita State University (Wichita, Kansas).

**WIND USERS MANUAL**

Snyder, M. H.

SERI/SP-732-728, 1980, National Renewable Energy Laboratory (Golden, Colorado).

**THE MOD-2 WIND TURBINE DEVELOPMENT PROJECT**

Solar Energy Research Institute (now National Renewable Energy Laboratory)

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 79-88.

**WTG ENERGY SYSTEMS' MP1-200 200-KILOWATT WIND TURBINE GENERATOR**

Spaulding, A. P. Jr.

The preliminary design criteria utilized for the MP1-200, the only wind turbine in operation at this time that is producing synchronous alternating current using a fixed pitch rotor configuration, are discussed. Installed on Cuttyhunk Island, Massachusetts, this machine became operational in June, 1977. In addition to design criteria, subjects covered are a description of the wind turbine, performance and operational experience, cost, and future R&D requirements and suggestions.

predicting dynamic loads in 11 HAWT rotor configurations with rated powers from 50 to 4000 kW. Data are presented in Part I [Spera, *et al.* 1987] and empirical equations are given in Part II [Spera 1993]. The present paper shows how to use these empirical equations to create design trend charts for rapidly estimating cyclic load levels vs their probability of exceedance, permitting engineers to assess fatigue loads early in the conceptual design process and to calibrate structural dynamic computer models. While valid for the given HAWT data set, these charts are offered as preliminary design guides only.

Proceedings, Windpower '93 Conference, 1993, American Wind Energy Association (Washington, DC), pp. 282-289.

## **DYNAMIC LOADS IN HORIZONTAL-AXIS WIND TURBINES, PART II: EMPIRICAL EQUATIONS**

Spera, D. A.

This study analyzes dynamic loads measured on a wide variety of medium- and large-scale HAWTs to create empirical equations with which to estimate cyclic load spectra for fatigue design purposes and to serve as a comparison for field test data. The loads data base, from HAWT R&D projects at the NASA Lewis Research Center, is summarized, including 11 two-bladed rotor configurations with power ratings from 50 kW to 4000 kW, three tower designs, and eight different sites. Four empirical equations are presented for predicting spectra of generator cyclic power; blade cyclic flatwise bending loads; blade cyclic chordwise bending loads; and cyclic rotor thrust. Standard deviations between calculations and test data are 20% for generator cyclic power, 10% for blade cyclic flatwise bending, 5% for blade cyclic chordwise bending, and an estimated 12% for rotor cyclic thrust. (See D. A. Spera *et al.*, Part I, 1987, with same title for data).

Proceedings, Windpower '92 Conference, 1992, American Wind Energy Association (Washington, DC), pp. 231-238.

## **PERFORMANCE OF THE 3.2-MW MOD-5B HORIZONTAL-AXIS WIND TURBINE DURING 55 MONTHS OF COMMERCIAL OPERATION IN HAWAII**

Spera, D. A., and Miller, M. W.

The purpose of this paper is to transfer to the wind energy community the unique performance and maintenance information on this multi-megawatt HAWT which has been provided to the Department of Energy for five years by Hawaiian Electric Renewable Systems, owners and operators of the Mod-5B. Operating history of the Mod-5B to date is summarized and documented, with comparisons of observed performance to design predictions. Subjects covered include energy production, correlation of mean operating power with annual average wind speed, availability of equipment, downtime attributed to failures in various turbine components, major maintenance events, utility outages and curtailments, and modifications made by HERS to the wind turbine system. Mean operating power is determined to be about 6.4% higher than design, with little change from the 7.5% increase measured during acceptance testing in 1987.

91N10127 NASA-RP-1236 DOE/NASA/20320-76

## **STRUCTURAL PROPERTIES OF LAMINATED DOUGLAS FIR/EPOXY COMPOSITE MATERIAL**

Spera, D. A., Esgar, J. B., Gougeon, M., and Zuteck, M. D.

This publication contains a compilation of static and fatigue strength data for laminated-wood material made from Douglas fir and epoxy. Results of tests conducted by several organizations are correlated to provide insight into the effects of variables such as moisture, size, lamina-to-lamina joint design, wood veneer grade, and the ratio of cyclic stress to steady stress during fatigue testing. These test data were originally obtained during development of wood rotor blades for large-scale wind turbines of the horizontal-axis (propeller) configuration. Most of the strength property data in this compilation are not found in the published literature. Test sections ranged from round cylinders 2.25 in. in diameter to rectangular slabs 6 by 24 in. in cross section and approximately 30 ft. long. All specimens were made from Douglas fir veneers 0.10 in. thick, bonded together with the WEST epoxy system developed for fabrication and repair of wood boats. Loading was usually parallel to the grain. Size effects (reduction in strength with increase in test volume) are observed in some of the test data, and a simple mathematical model is presented that includes the probability of failure. General characteristics of the wood/epoxy laminate are discussed, including features that make it useful for a wide variety of applications.

88N22429 Proceedings, Lewis Structures Technology Conference, Volume 3, 1988, NASA CP 3003, pp. 285-297; also Proceedings, Windpower '88 Conference, 1988, American Wind Energy Association (Washington, DC), pp. 329-338.

## **LARGE-SCALE WIND TURBINE STRUCTURES**

Spera, D. A.

The purpose of this presentation is to show how structural technology was applied in the design of modern wind turbines, which were recently brought to an advanced stage of development as sources of renewable power. Wind turbine structures present many difficult problems because they are relatively slender and flexible; subject to vibration and aeroelastic instabilities; acted upon by loads which are often non-deterministic; operated continuously with little maintenance in all weather; and dominated by life-cycle cost considerations. Progress in horizontal-axis wind turbines (HAWT) development was paced by progress in the understanding of structural loads, modeling of structural dynamic response, and designing of innovative structural response. During the past 15 years a series of large HAWTs was developed. This has culminated in the recent completion of the world's largest operating wind turbine, the 3.2 MW Mod-5B power plane installed on the island of Oahu, Hawaii. Some of the applications of structures technology to wind turbine will be illustrated by referring to the Mod-5B design. First, a video overview will be presented to provide familiarization with the Mod-5B project and the important components of the wind turbine system. Next, the structural requirements for large-scale wind turbines will be discussed, emphasizing the difficult fatigue-life requirements. Finally, the procedures used to design the structure will be presented, including the use of the fracture mechanics approach for determining allowable fatigue stresses.

Proceedings, Seventh ASME Wind Energy Symposium, SED-Vol. 5, 1988, American Society of Mechanical Engineers (New York), pp. 69-70.

#### **INITIAL OPERATION AND TESTING OF THE DOE/NASA 3.2-MW MOD-5B WIND TURBINE**

Spera, D. A.

This presentation documents the significant technical features in the Mod-5B design, including its variable-speed generating system, and discusses the results of tests conducted to determine power output and quality, structural dynamic behavior, and initial reliability of components. The test program, with at least 1000 hours of operation, is composed of three separate tests: An operational test (500 hr, min.), a performance test (500 hr, min.), and a structural integrity test (18 hr, min., during the performance test). Voltage harmonics on the 46 kV line and a preliminary power curve are illustrated.

Proceedings, Windpower '87 Conference, 1987, American Wind Energy Association (Washington, DC), SERI/CP-217-3315, National Renewable Energy Laboratory (Golden, Colorado), pp. A-H.

#### **SYMPOSIUM ON WIND TURBINE TECHNOLOGY**

Spera, D. A.

Authors contributing to a book on wind turbine technology, sponsored by ASME and DOE, present overviews of their individual chapters, as follows: Evolution of Modern Wind Turbines (L. V. Divone, D. G. Shepherd); Current Wind Turbine Systems and Applications (R. Lynette and P. Gipe); Siting Considerations (H. H. Hubbard, K. P. Shepherd, D. L. Sengupta, T. B. A. Senior); Aerodynamic Behavior of Wind Turbines (R. E. Wilson, P. B. S. Lissaman); Characteristics of the Wind (W. Frost, C. Aspliden); and Structural Dynamic Behavior of Wind Turbines (L. P. Mirandy, G. S. Doman).

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 457-462.

#### **DYNAMIC LOADS IN LARGE HORIZONTAL-AXIS WIND TURBINES -- PART I: FIELD TEST DATA**

Spera, D. A., Ensworth, C. B. F. III, and Janetzke, D. C.

This study summarized experience with predicting and measuring dynamic loads in 8 HAWTs with rated powers from 50 to 4000 kW. Part I documents measured loads for 13 combinations of rotor configuration, wind turbine, and test site. In following parts, data will be examined to identify trends in the magnitudes of dynamic loads vs turbine size, type, and site, and to develop empirical equations with which to estimate fatigue loads. Sample size is 975,000 rotor revolutions of data, for which four parameters are presented: Free-stream wind speed, cyclic torque, cyclic flatwise blade bending moment, and cyclic chordwise blade bending moment. A small sample of cyclic tower bending moments is also presented. A statistical analysis is used, with the largest variance in cyclic torque, which was twice that of the wind speed. (See D. A. Spera, 1993, for Part II and 1994 for Part III.)

Proceedings, Sixth ASME Wind Energy Symposium, SED-Vol. 3, 1987, American Society of Mechanical Engineers (New York), pp. 41.

#### **PREVIEW OF THE ASME/DOE WIND TURBINE TECHNOLOGY BOOK**

Spera, D. A.

Plans for a book, co-sponsored by the American Society of Mechanical Engineers and the U.S. Department of Energy, which will present a comprehensive review of the state-of-the-art in wind turbine technology are discussed. Subjects such as the evolution of modern wind turbines, current wind turbine systems and applications, characteristics of the wind, aerodynamic behavior of wind turbines, structural dynamic behavior of wind turbines, wind turbine effects on the environment,

and HAWT and VAWT design topics are included.

**87A25475** ASME Paper 86-JPGC-PTC-4; Presented at ASME/IEEE Joint Power Generation Conference, 1986, 9 pp.  
**OVERVIEW OF THE NEW ASME PERFORMANCE TEST CODE FOR WIND TURBINES**

Spera, D. A.

The principal technical features of the ASME Performance Test Code for wind turbines are presented and such issues as what sizes and types of wind turbines should be included, what the principal measure of performance should be, and how wind speed should be measured are discussed. It is concluded that the present test code is applicable to wind turbine systems of all sizes. The principal measure of performance as defined by this code is net energy output, and the primary performance parameter is the "test energy ratio" which is based on a comparison between the measured and predicted energy output for the test period.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 639-648.

**ENERGY METHOD FOR EVALUATING WIND TURBINE-GENERATOR PERFORMANCE**

Spera, D. A.

This paper describes a simplified method for measuring and assessing wind turbine performance under random wind conditions. The proposed procedure is termed the "energy method" because it is based on measurements of energy production during intervals of time, rather than on measurements of instantaneous power. This significantly simplifies taking and reducing test data, integrates effects of varying winds, minimizes data scatter, and assesses performance directly in terms of the systems primary function: the long-term production of energy. Test data requirements, equations for data analysis, and a sample test based on performance data from Mod-2 2.5-MW HAWTs.

**83N19255** Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 447-467.

**PERFORMANCE AND LOAD DATA FROM MOD-0A AND MOD-1 WIND TURBINE GENERATORS**

Spera, D. A. , and Janetzke, D. C.

Experimental data, together with supporting analysis, are presented on the power conversion performance and blade loading of large, horizontal-axis wind turbines tested at electric utility sites in the U.S. Four turbine rotor configurations, from 28 to 61 meters in diameter, and data from five test sites are included. Performance data are presented in the form of graphs of power and system efficiency versus free-stream wind speed. Deviations from theoretical performance are analyzed statistically. Power conversion efficiency averaged 0.34 for all tests combined, compared with 0.31 predicted. Round blade tips appeared to improve performance significantly. Cyclic blade loads were normalized to develop load factors which can be used in the design of rotors with rigid hubs.

**82N23699** Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 139-150.  
**CALCULATION OF GUARANTEED MEAN POWER FROM WIND TURBINE GENERATORS**

Spera, D. A.

A method for calculating the "guaranteed mean" power output of a wind turbine generator is proposed. The term "mean power" refers to the average power generated at specified wind speeds during short-term tests. Correlation of anemometers, the method of bins for analyzing non-steady data, the PROP Code for predicting turbine power, and statistical analysis of deviations in test data from theory are discussed. Guaranteed mean power density for the Clayton Mod-0A system was found to be 8 watts per square meter less than theoretical power density at all power levels, with a confidence level of 0.999. This amounts to 4 percent of rated power.

**80A35719** and **80N13623** NASA-TM-79275 DOE/NASA/1059-79/4, 1979; also Proceedings, Conference and Workshop on Wind Energy Characteristics and Wind Energy Siting, 1979, American Meteorological Society (Boston, Massachusetts) pp. 47-58.

**MODIFIED POWER LAW EQUATIONS FOR VERTICAL WIND PROFILES**

Spera, D. A. , and Richards, T. R.

In an investigation of windpower plant siting, equations are presented and evaluated for a wind profile model which incorporates both roughness and wind speed effects, while retaining the basic simplicity of the Hellman power law. These equations recognize the statistical nature of wind profiles and are compatible with existing analytical models and recent wind profile data. Results are evaluated by comparison with wind profile data measured at a variety of sites. Predictions of energy output based on the proposed profile equations are 10% to 20% higher than those made with the 1/7 power law. In addition,

correlation between calculated and observed blade loads is significantly better at higher wind speeds when the proposed wind profile model is used than when a constant power model is used.

**80N16494** NASA-TM-81408 DOE/NASA/1010-79/5, 1979; also Proceedings, Fourth Wind Energy Workshop, 1979, DOE CONF 791097, JBF Scientific (Washington, DC), pp. 99-117.

#### **PRELIMINARY ANALYSIS OF PERFORMANCE AND LOADS DATA FROM THE 2-MEGAWATT MOD-1 WIND TURBINE GENERATOR**

Spera, D. A. , Viterna, L. A. , Richards, T. R. , and Neustadter, H. E.

Preliminary test data on output power vs wind speed, rotor blade loads, system dynamic behavior, and start-stop characteristics on the 61-m diameter Mod-1 HAWT are presented which were measured during its initial operation in August, September, and October of 1979. These data were analyzed statistically and are compared with design predictions of system performance and loads. To date, the Mod-1 wind turbine generator has produced up to 1.5 MW of power, with a measured power versus wind speed curve which agrees closely with design. Blade loads were measured at wind speeds up to 14 m/s and also during rapid shutdowns. Peak transient loads during the most severe shutdowns are less than the design limit loads. On the inboard blade sections, fatigue loads are approximately equal to the design cyclic loads. On the outboard blade sections, however, measured cyclic loads are significantly larger than design values, but they do not appear to exceed fatigue allowable loads as yet. The causes of these higher loads and their effect on long-time fatigue life are still being determined.

**80N16469** Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 211-224.

#### **STRUCTURAL ANALYSIS CONSIDERATIONS FOR WIND TURBINE BLADES**

Spera, D. A.

Approaches to the structural analysis of wind turbine blade designs are reviewed. Specifications and materials data are discussed along with the analysis of vibrations, loads, stresses, and failure modes.

**80N16455** Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 25-33.

#### **DESIGN EVOLUTION OF LARGE WIND TURBINE GENERATORS**

Spera, D. A.

During the past five years, the goals of economy and reliability have led to a significant evolution in the basic design--both external and internal--of large wind turbine systems. To show the scope and nature of recent changes in wind turbine designs, development of three types are described: (1) system configuration developments; (2) computer code developments; and (3) blade technology developments.

**78A37678, 78N23556, and 78N19617** NASA-TM-73773 DOE/NASA/1028-78/16, 1977; also Summaries in Proceedings, Third Wind Energy Workshop, Volume 2, 1977, DOE CONF 770921, JBF Scientific (Washington, DC), pp. 502-516, and Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 1-13.

#### **COMPARISON OF COMPUTER CODES FOR CALCULATING DYNAMIC LOADS IN WIND TURBINES**

Spera, D. A.

The development of computer codes for calculating dynamic loads in horizontal axis wind turbines was examined, and a brief overview of the seven codes in the study was given. All codes are aeroelastic and include loads which are gravitational, inertial and aerodynamic in origin. Four of the seven codes include rotor-tower interaction and three are limited to rotor analysis. Mean and cyclic blade bending moment loads calculated with each code were compared against two sets of test data measured on a 100 kW Mod-0 wind turbine. Accuracy was judged on the basis of cyclic loads, peak loads, and harmonic contents. With a few exceptions, all calculated loads were within 25% of nominal test data.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 275-283.

#### **THE BRUSH WIND TURBINE GENERATOR AS DESCRIBED IN SCIENTIFIC AMERICAN OF DECEMBER 20, 1890**

Spera, D. A.

An historic wind turbine generator is described which operated in Cleveland, Ohio, from 1888 to 1908. The machine had a 144-blade rotor 56 feet in diameter, a pivoted tower 60 feet high, and a maximum output of 12 kW DC. This turbine is thought to represent the first juncture of the highly-developed windmill technology and the newly-emerging technology of

electrical power generation.

**78A20476 and 78N19636** Wind Technology Journal, Volume 1, Summer 1977, pp. 5-10; and Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 227-236.

**EFFECTS OF ROTOR LOCATION, CONING, AND TILT ON CRITICAL LOADS IN LARGE WIND TURBINES**  
Spera, D. A. , and Janetzke, D. C.

Three large (1,500 kW) horizontal-axis rotor configurations were analyzed to determine the effects on dynamic loads of upwind and downwind rotor locations, coned and radial blade positions, and tilted and horizontal rotor axis positions. Loads were calculated for a range of wind velocities at three locations in the structure: the blade shank, the hub shaft, and the yaw drive. Blade axis coning and rotor axis tilt were found to have little effect on loads. However, locating the rotor upwind of the tower significantly reduced loads at all locations analyzed.

**77N30599** NASA-TM-73711 ERDA/NASA-1004/77/2, 1977; also Proceedings, National Conference of American Wind Energy Association, May 1977.

**DYNAMIC BLADE LOADING IN THE ERDA/NASA 100 KW AND 200 KW WIND TURBINES**

Spera, D. A. , Janetzke, D. C. , and Richards, T. R.

Dynamic blade loads, including aerodynamic, gravitational, and inertial effects, are presented for two large horizontal-axis wind turbines: The ERDA-NASA 100-kW Mod-0 and 200-kW Mod-0A wind power systems. Calculated and measured loads are compared for an experimental Mod-0 machine in operation. Predicted blade loads are also given for the higher power Mod-0A wind turbine now being assembled for operation as part of a municipal power plant. Two major structural modifications have been made to the Mod-0 wind turbine for the purpose of reducing blade loads. A stairway within the truss tower was removed to reduce the impulsive aerodynamic loading caused by the tower wake on the downwind rotor blades. Also, the torsional stiffness of the yaw drive mechanism connecting the turbine nacelle to the tower was doubled to reduce rotor-tower interaction loads. Measured reductions in load obtained by means of these two modifications equaled or exceeded predictions.

**76A28234 and 75N17712** NASA-TM-X-3198 ERDA/NASA/1004-77/4, 1975; also Proceedings, Workshop on Advanced Wind Energy Systems, Volume 2, 1974, National Swedish Board for Technical Development and Swedish State Power Board (Stockholm), pp. 2-63 to 2-99.

**STRUCTURAL ANALYSIS OF WIND TURBINE ROTORS FOR NSF-NASA MOD-0 WIND POWER SYSTEM**  
Spera, D. A.

Preliminary estimates are presented of vibratory loads and stresses in two rotors proposed for the 100 kW NSF-NASA Mod-0 wind power system. Each rotor has two 19-m (62.5-ft) blades, but one hub is hingeless while the other is teetering. Preliminary blade design utilizes a tapered tubular aluminum spar which supports nonstructural aluminum ribs and skin and is joined to the rotor hub by a steel shank tube. Stresses in the shanks of the blade in the two rotor designs are calculated for static, rated, and overload operating conditions. Blade vibrations were limited to the fundamental flapping modes, which were elastic cantilever bending for hingeless rotor blades and rigid-body rotation for teetering rotor blades. The MOSTAB-C computer code was used to calculate aerodynamic and mechanical loads. The teetering rotor has substantial advantages over the hingeless rotor with respect to shank stresses, fatigue life, and tower loading. The hingeless rotor analyzed does not appear to be structurally stable during overloads. A teetering rotor will probably be required in order to achieve a long service life in a large wind turbine exposed to periodic overload conditions.

NASA-CR-174981 DOE/NASA/0247-1, 1985.

**WEST-3 WIND TURBINE SIMULATOR DEVELOPMENT -- VOLUME 1: SUMMARY**  
Sridhar, S.

NASA-CR-174982 DOE/NASA/20320-71, 1985.

**WEST-3 WIND TURBINE SIMULATOR DEVELOPMENT -- VOLUME 2: VERIFICATION**  
Sridhar, S.

Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 15-29.

**MOD-1 WTG DYNAMIC ANALYSIS**  
Stahle, C. V. Jr.

This paper discusses the dynamic analysis of the Mod-1 2000 kW horizontal-axis wind turbine. After briefly describing

the Mod-1 design, the dynamic analysis used to evaluate the dynamic loads and structural interactions is discussed. The resonant frequency placement, the treatment of unsteady wind loading and the dynamic load sensitivity to frequency shifts are reviewed for the design.

NASA-TT-F-15,349 and -15,353, 1974 Technical Translation.

# **IMPORTANCE AND PROGRESS OF WIND POWER UTILIZATION IN DENMARK**

Stein, D.

NASA-TT-F-15,345, Technical Translation.

# **UTILIZATION OF WIND POWER IN AGRICULTURE IN THE USSR**

Stein, D.

NASA-TT-F-15,338, Technical Translation.

# **AIR POWER PLANTS IN RUSSIA AND THE UNITED STATES**

Stein, D.

NASA-TM-83288, 1982.

# **GUIDE TO THE EVALUATION OF HUMAN EXPOSURE TO NOISE FROM LARGE WIND TURBINES**

Stephens, D. G. , Shepherd, K. P. , Hubbard, H. H. , and Grosveld, F. W.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 431-435.

# **WIND TURBINE ACOUSTIC STANDARDS**

Stephens, D. G. , Shepherd, K. P. , and Grosveld, F.

A program is being conducted to develop noise standards for wind turbines which minimize annoyance and which can be used in design specifications. The approach consists of presenting wind turbine noise stimuli to test subjects in a laboratory listening chamber. Responses of the subjects are recorded for a range of stimuli which encompass the designs, operating conditions, and ambient noise levels of current and future installations. Results to date have established the threshold of detectability for a range of impulsive stimuli of the type associated with blade/tower wake interactions. The status is described of ongoing psychoacoustic tests, the subjective data, and the development of acoustic criteria and standards.

83A36410 IEEE Transactions on Power Apparatus and Systems, Volume PAS-102, June 1983, Institute of Electrical and Electronic Engineers, p. 1788-1792.

# **MEASURED EFFECT OF WIND GENERATION ON THE FUEL CONSUMPTION OF AN ISOLATED DIESEL POWER SYSTEM**

Stiller, P. H. , Scott, G. W. , and Shaltens, R. K.

The Block Island Power Company (BIPCO), on Block Island, Rhode Island, operates an isolated electric power system consisting of diesel generation and an experimental wind turbine. The 150-kW wind turbine, designated Mod-0A by the U.S. Department of Energy is typically operated in parallel with two diesel generators to serve an average winter load of 350 kW. Wind generation serves up to 60 percent of the system demand depending on wind speed and total system load. Results of diesel fuel consumption measurements are given for the diesel units operated in parallel with the wind turbine and again without the wind turbine. The fuel consumption data are used to calculate the amount of fuel displaced by wind energy. Results indicate that the wind turbine displaced 25,700 lbs. of the diesel fuel during the test period, representing a calculated reduction in fuel consumption of 6.7 percent while generating 11 percent of the total electric energy. The amount of displaced fuel depends on operating conditions and system load. It is also shown that diesel engine throttle activity resulting from wind gusts which rapidly change the wind turbine output do not significantly influence fuel consumption.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 62-69.

# **WIND DATA FOR WIND DRIVEN PLANT**

Stodhart, A. H.

HSE-10805, 1986, Hamilton Standard Division (Windsor Locks, Connecticut)

# **AN EVALUATION OF TURBULENCE-INDUCED FATIGUE LOADS SUSTAINED BY A LARGE-SCALE, COMPLIANT HAWT ROTOR**

Stoltze, C. L.

NASA-CR-159779, 1980.

**DOE/NASA WIND TURBINE DATA ACQUISITION SYSTEM -- PART 2, OPERATION AND MAINTENANCE**  
Strock, O. J.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society  
(Boulder, Colorado), pp. 649-651.

**PP&L OPERATIONAL EXPERIENCE WITH A 200 kW RESEARCH WIND TURBINE**

Stultz, C. D. , and Neustadter, H. E.

Data from performance tests of an MP-200 HAWT at Whiskey Run, Oregon, are analyzed for the effect of yaw error on the power curve. Analysis of the clockwise and counter-clockwise yaw errors indicated that the control anemometer located 10 diameters (800 ft) east of the turbine could possibly be introducing spatial variation type yaw error into the test data. Adjusting the data for suspected errors resulted in a cosine cubed relationship between rotor power and yaw error, for the same wind speed.

Proceedings, Windpower '88 Conference, 1988, American Wind Energy Association (Washington, DC),  
pp. 260-269.

**HEI'S WIND FARM CONTROL EXPERIENCE**

Suehiro, D. , and Miller, M. W.

Control and monitoring systems for the 12.2-ME Kahuku wind power station on Oahu in the Hawaiian Islands are described. Computer display screens at the central control facility are illustrated, showing information for operation and control, set points, faults, and instantaneous and cumulative data. Conclusions are drawn as to the benefits of central control and the Westinghouse CCU software, including finding problems before they become major, troubleshooting, preparing for and scheduling repairs of faults, and failure analysis. Meter data is considered to be very important for accurate accounting and statistical study of individual turbines and the power station as a whole.

84N29347 NASA-TM-83680 DOE/NASA/20320-59, 1984.

**EFFECT OF VORTEX GENERATORS ON THE POWER CONVERSION PERFORMANCE AND STRUCTURAL DYNAMIC LOADS OF THE MOD-2 WIND TURBINE**

Sullivan, T. L.

Applying vortex generators from 20 to 100 percent span of the Mod-2 rotor resulted in a projected increase in annual energy capture of 20 percent and reduced the wind speed at which rated power is reached by nearly 3 m/sec. Application of vortex generators from 20 to 70 percent span, the fixed portion of the Mod-2 rotor, resulted in a projected increase in annual energy capture of about half this. This improved performance came at the cost of a small increase in cyclic blade loads in below rated power conditions. Cyclic blade loads were found to correlate well with the change in wind speed during one rotor revolution.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society  
(Boulder, Colorado), pp. 173-179.

**LABORATORY AND FIELD TESTING OF A FIBERGLASS ROTOR BLADE FOR THE MOD-0A 200 KW WIND TURBINE**

Sullivan, T. L.

Fatigue tests were performed on full- and half-scale root end sections, first to qualify the root retention design, and second to induce failure. Test methodology and results are presented. Two operational blades were proof tested to design limit load to ascertain buckling resistance. Measurements of natural frequency, damping ratio, and deflection under load made on the operational blades are documented. The tests showed that all structural design requirements were met or exceeded. Blade loads measured during 3000 hr of field operation were close to those expected. The measured loads validated the loads used in the fatigue tests and gave high confidence in the ability of the blades to achieve design life.

83N23710 NASA-TM-83309 NASA/DOE/20320-44, 1983.

**STRUCTURAL QUALIFICATION TESTING AND OPERATIONAL LOADING ON A FIBERGLASS ROTOR BLADE FOR THE MOD-0A WIND TURBINE**

Sullivan, T. L.

Fatigue tests were performed on full- and half-scale root end sections, first to qualify the root retention design, and second to induce failure. Test methodology and results are presented. Two operational blades were proof tested to design limit load to ascertain buckling resistance. Measurements of natural frequency, damping ratio, and deflection under load made

on the operational blades are documented. The tests showed that all structural design requirements were met or exceeded. Blade loads measured during 3000 hr of field operation were close to those expected. The measured loads validated the loads used in the fatigue tests and gave high confidence in the ability of the blades to achieve design life.

**83A13696 and 82N23711** Solar Energy, Volume 29, Number 5, 1982, p. 377-383; and Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 237-244.

#### **A REVIEW OF RESONANCE RESPONSE IN LARGE, HORIZONTAL-AXIS WIND TURBINES**

Sullivan, T. L.

Loads and resonances measured during field operations of the Mod-0 (100-kW) and Mod-1 (2,000 kW) wind turbines are described, and measured system natural frequencies are compared with design values. The design approach employed to avoid resonances in the Mod-2 (2,500 kW) wind turbine is presented. Mod-0 and Mod-1 operational experience shows that 1 per rev excitation exists in the drive train, high aerodynamic damping prevents resonance response of the blade flatwise modes, and teetering the hub substantially reduces the chordwise blade response to odd harmonic excitation. These results can be used by designers as a guide to system frequency placement. In addition, it is found that present analytical techniques can accurately predict wind turbine natural frequencies.

**80N16472** Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 267-284.

#### **DESIGN, FABRICATION, AND TEST OF A STEEL SPAR WIND TURBINE BLADE**

Sullivan, T. L. , Sirocky, P. J. , and Viterna, L. A.

The design and fabrication of wind turbine blades based on 60-foot low-cost steel spars are discussed. Performance and blade load information is given and compared to analytical prediction. In addition, performance is compared to that of the original Mod-0 aluminum blades. Costs for building the two blades are given, and a projection is made for the cost in mass production. Design improvements to reduce weight and improve fatigue life are suggested.

**79A20828 and 78N17466** NASA-TM-73835 DOE/NASA/1028-77/13; also Proceedings, 23rd National Symposium and Exhibition, 1978, Society for the Advancement of Material and Process Engineering, pp. 428-456.

#### **WIND-TURBINE-GENERATOR ROTOR-BLADE CONCEPTS WITH LOW-COST POTENTIAL**

Sullivan, T. L. , Cahill, T. P. , Griffec, D. G. Jr. , and Gewehr, H. W.

Four processes for producing blades are examined. Two use filament winding techniques and two involve filling a mold or form to produce all or part of a blade. The processes are described and a comparison is made of costs, material properties, designs and free vibration characteristics. Conclusions are made regarding the feasibility of each process to produce low-cost, structurally adequate blades.

**78N19619** Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 31-37.

#### **SIMPLIFIED MODELING FOR WIND TURBINE MODAL ANALYSIS USING NASTRAN**

Sullivan, T. L.

A detailed finite element model of the Mod-0 wind turbine tower was reduced to six beam elements (stick model). The method used to calculate the properties of the beam elements in the stick model was explained and the accuracy of the stick model in predicting natural frequencies and mode shapes was examined. Computer times were compared and several applications where the stick model was used are described. From results obtained from the Mod-0 tower it is concluded that a tower of this type can be modeled as a simple cantilever beam for modal analysis. However, this model should be limited to tower torsional modes and tower bending modes where the mode shape resembles a cantilever beam first bending mode shape. Use of this model reduces the computer time required for modal analysis.

**77N30611** NASA-TM-73718 ERDA/NASA-1028/77/1, 1977.

#### **DRIVE TRAIN NORMAL MODES ANALYSIS FOR THE ERDA/NASA 100-KILOWATT WIND TURBINE GENERATOR**

Sullivan, T. L. , Miller, D. R. , and Spera, D. A.

Natural frequencies, as a function of power were determined using a finite element model. Operating conditions investigated were operation with a resistive electrical load and operation synchronized to an electrical utility grid. The influence of certain drive train components on frequencies and mode shapes is shown. An approximate method for obtaining drive train natural frequencies is presented.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111. pp. 185-192.

#### **OVERVIEW OF VERTICAL AXIS WIND TURBINE (VAWT) BLADE DESIGN PROCEDURES**

Sullivan, W. N.

A survey is presented of the practices which have been applied for designing VAWT blades in the past, with a discussion of strengths and weaknesses. Planned or suggested future work in developing improved aerodynamic and structural design tools is also discussed.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111. pp. 205-210.

#### **OPERATIONAL EXPERIENCE WITH VAWT BLADES AT SANDIA LABORATORIES**

Sullivan, W. N.

This paper discusses primarily blade structural performance and vibratory stress aspects of the tests on the 17 meter VAWT rotor.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 79-86.

#### **PERFORMANCE OF WIND TURBINES IN A TURBULENT ATMOSPHERE**

Sundar, R. M. , and Sullivan, J. P.

Effects of atmospheric turbulence on power fluctuations of large wind turbines are discussed, with emphasis on spatial non-uniformities of the wind. Turbulent winds with correlation in time and space are simulated on the computer by the Shinozuka's method, modelled according to the Davenport spectrum with an exponential spatial correlation function. Rotor aerodynamics are modeled by simple blade element theory. Comparison of the spectra of power output signals between 1-D and 3-D turbulence shows significant power fluctuations centered around the blade passage frequency.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006,  
pp. 70-72.

#### **AN INTRODUCTION TO THE PRINCETON SAILWING WINDMILL**

Sweeney, T. E. , and Nixon, W. B.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006,  
pp. 152-154.

#### **ENERGY STORAGE BY COMPRESSED AIR**

Szego, G. C.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 35-40.

#### **HORIZONTAL AXIS WIND TURBINE POST-STALL AIRFOIL CHARACTERISTICS SYNTHESIZATION**

Tangler, J. L. , and Ostowari, C.

This paper addresses a weakness in computer models used to predict the output power of wind turbines on the basis of blade-element/momentum theory, which is their inability to consistently predict the peak power of a stall-controlled rotor. This paper compares measured power curves of the Mod-0 experimental HAWT to performance predictions made using two of the more popular codes, namely the PROPSHAFT and WIND II codes. Special emphasis is given to the technique used to predict peak power, and a newly-developed model for synthesizing post-stall lift and drag curves is presented. This model is based on results of comprehensive wind tunnel tests in which the effects of aspect ratio, airfoil thickness, and Reynolds were investigated.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979,  
NASA CP 2106, DOE CONF-7904111. pp. 143-154.

#### **DESIGN CHARACTERISTICS OF THE 224 KW MAGDALEN ISLANDS VAWT**

Templin, R. J.

The evolution of the main design features of the Magdalen Islands VAWT is described. The turbine has a rotor height of 120 ft (36.58 m) and diameter of 80 ft (24.38 m). It was operated as a joint project between NRC and Hydro-Quebec in grid-coupled mode from July 1977 to July 1978 when the rotor was destroyed in an accident. The rotor is being rebuilt with minor modifications and some directions for future VAWT research are suggested.

NASA-CR-165463 DOE/NASA/0101-1, 1982.

**DESIGN AND EVALUATION OF LOW-COST LAMINATED WOOD COMPOSITE BLADES FOR INTERMEDIATE SIZE WIND TURBINES: BLADE DESIGN, FABRICATION CONCEPT, AND COST ANALYSIS**  
Thomas, G., Gougeon, M., Zuteck, M. D., and Lieblein, S.

**83N15911 and 82N16495** NASA-TM-82761 DOE/NASA/20305-7, 1981; also Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. I, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 39-57.

**THE NASA LEWIS LARGE WIND TURBINE PROGRAM**

Thomas, R. L. , and Baldwin, D. H.

The large wind turbine program activities are reviewed. The program is directed toward development of the technology for safe, reliable, environmentally acceptable large wind turbines that have the potential to generate a significant amount of electricity at costs competitive with conventional electric generation systems. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements. Advances are made by gaining a better understanding of the system design drivers, improvements in the analytical design tools, verification of design methods with operating field data, and the incorporation of new technology and innovative designs. These activities include results from the first and second generation field machines (200-kW Mod-0A, 2,000 kW Mod-1, and 2,500-kW Mod-2), the design phase of the third generation wind turbine (multi-megawatt Mod-5) and advanced research and technology projects. The status of the WTS-4 machine (4,000 kW), sponsored by the U.S. Department of the Interior, is also presented.

**83N14690** NASA-TM-82991 DOE/NASA/20320-42, 1982; presented at National Rural Electric Cooperatives Association and DOE Rural Electric Wind Energy Workshop, 1982.

**DOE/NASA LEWIS LARGE WIND TURBINE PROGRAM**

Thomas, R. L.

An overview of the large wind turbine activities managed by NASA is given. These activities include results from the first and second generation field machines (200-kW Mod-0A, 2,000 kW Mod-1, and 2,500-kW Mod-2), the status of the Department of Interior 4,000-kW WTS-4 machine, for which NASA provides technical management, and the design phase of the third generation wind turbines (multi-megawatt Mod-5).

**81A23694** Journal of Industrial Aerodynamics, Volume 5, May 1980, p. 323-335.

**LARGE WIND-TURBINE PROJECTS IN THE UNITED STATES WIND ENERGY PROGRAM**

Thomas, R. L. , and Robbins, W. H.

The technological development of large, horizontal-axis wind turbines (100 kW-2500 kW) is surveyed with attention to prototype projects managed by NASA. Technical feasibility has been demonstrated in utility service by four Mod-0A wind turbine systems with rated power of up to 200 kW and a rotor diameter of 125 ft. Current designs of large wind turbines such as the 2,500-kW Mod-2 are projected to be cost competitive for utility applications when produced and operated in quantity, with capital costs of 600 to 700 dollars per installed kW (in 1977 dollars).

Proceedings, Fourth Biennial Conference and Workshop on Wind Energy Conversion Systems, 1979, DOE CONF-791097, JBF Scientific (Washington, DC), pp. 75-97.

**LARGE WIND TURBINE PROJECTS**

Thomas, R. L. , and Robbins, W. H.

This paper summarizes the current designs, hardware, supporting research, operating experience, and cost projections for large-scale HAWTs in the NASA/DOE wind turbine program. Since 1973, significant advances have been made in the technology leading to megawatt-scale turbines. Five intermediate-scale machines are now operating on utility grids. The development of the Mod-0, Mod-0A, Mod-1, and Mod-2 HAWTs is described.

Proceedings, Fourth Biennial Conference and Workshop on Wind Energy Conversion Systems, 1979, DOE CONF-791097, JBF Scientific (Washington, DC), pp. 137-149.

**KEY ISSUES ASSOCIATED WITH LARGE SCALE SYSTEMS**

Thomas, R. L.

Issues developed through discussions with wind turbine developers, utility personnel, personnel from the Electric Power Research Institute, and government project and program managers are presented, divided into the following categories: Technology readiness, potential for significant energy impact, user acceptance, creation of a competitive wind turbine industry,

and public acceptance.

Proceedings, Fourth Biennial Conference and Workshop on Wind Energy Conversion Systems, 1979, DOE CONF-791097, JBF Scientific (Washington, DC), pp. 493-506.

#### **WORKING GROUP REPORT ON LARGE SCALE SYSTEMS: DESIGN AND R&D**

Thomas, R. L.

Topics discussed include optimum spacing of wind turbines, reliability and O&M, demonstration of 30-year hardware life, wind turbine/utility electrical interface, computer codes for performance and structural analyses, machine rating designation, environmental concerns, and basic machine characteristics.

**79A15881 and 78N29575** NASA-TM-73767 DOE/NASA/1059-78/1, 1978; also Proceedings, Fifth Energy Technology Conference and Exposition, 1978, Government Institutes, Inc. (Washington, DC), pp. 64-82.

#### **LARGE WIND TURBINE GENERATORS -- NASA PROGRAM STATUS AND POTENTIAL COSTS**

Thomas, R. L. , and Donovan, R. M.

The development associated with large wind turbine systems is briefly described. The large wind turbine portion of the Federal Wind Energy Program consists of two major project efforts: (1) the Mod-0 test bed project for supporting research technology, and (2) the large experimental wind turbines for electric utility applications. The Mod-0 has met its primary objective of providing the entire wind energy program with early operations and performance data. The large experimental wind turbines to be tested in utility applications include three of the Mod-0A (200 kW) type, one Mod-1 (2000 kW), and possibly several of the Mod-2 (2500 kW) designs. This paper presents a description of these wind turbine systems, their programmatic status, and a summary of their potential costs.

**78N76990** Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 13-20.

#### **INTRODUCTION TO LARGE SYSTEM DESIGN**

Thomas, R. L.

These projects represent that portion of the national five-year wind-energy program that is being managed by the NASA-Lewis Research Center for the Energy Research and Development Administration. Major concerns confronting designers of large WTG systems are (1) cost-effective configurations and sizes, (2) rotor life, (3) rotor/tower dynamic interactions, (4) controls for stable, automatic operation, and (5) the operating environment. Broader issues include system reliability, compatibility with utility networks, build-up of production capability, and transfer of technology from experimental projects to industry.

**78N15563** NASA-TM-73825 ERDA/NASA-1028/77/9, 1977; also Proceedings, Third Wind Energy Workshop, Volume 1, 1977, DOE CONF 770921, JBF Scientific (Washington, DC), pp. 35-58.

#### **ERDA/NASA 100 KILOWATT MOD-0 WIND TURBINE OPERATIONS AND PERFORMANCE AT THE NASA PLUM BROOK STATION, OHIO**

Thomas, R. L. , and Richards, T. R.

The ERDA/NASA 100 kW Mod-0 wind turbine is operating at the NASA Plum Brook Station near Sandusky, Ohio. The operation of the wind turbine has been fully demonstrated and includes start-up, synchronization to the utility network, blade pitch control for control of power and speed, and shut-down. Also, fully automatic operation has been demonstrated by use of a remote control panel, 50 miles from the site, similar to what a utility dispatcher might use. The operation systems and experience with the wind turbine loads, electrical power and aerodynamic performance obtained from testing are described.

**76A40452** Energy, Volume 1, Winter 1976, pp. 27-30.

#### **ERDA-NASA WIND ENERGY PROJECT READY TO INVOLVE USERS**

Thomas, R. , Puthoff, R. , Savino, J. , and Johnson, W.

The NASA contribution to the Wind Energy Project is discussed. NASA is responsible for the following: (1) identification of cost-effective configurations and sizes of wind-conversion systems, (2) the development of technology needed to produce these systems, (3) the design of wind-conversion systems that are compatible with user requirements, particularly utility networks, and (4) technology transfer obtained from the program to stimulate rapid commercial application of wind systems. Various elements of the NASA program are outlined, including industry-built user operation, the evaluation phase, the proposed plan and schedule for site selection and user involvement, supporting research and technology (e.g. , energy storage), and component and subsystem technology development.

**76N21683** NASA-TM-X-71890 ERDA/NASA/1010-77/3, 1976; also Proceedings, Third Energy Technology Conference and Exposition, 1976, Government Institutes, Inc. (Washington, DC).

**LARGE EXPERIMENTAL WIND TURBINES: WHERE WE ARE NOW**

Thomas, R. L.

Several large wind turbine projects have been initiated by NASA-Lewis as part of the ERDA wind energy program. The projects consist of progressively large wind turbine ranging from 100 kW with a rotor diameter of 125 feet to 1500 kW with rotor diameters of 200 to 300 feet. Also included is supporting research and technology for large wind turbines and for lowering the costs and increasing the reliability of the major wind turbine components. The results and status of the above projects are briefly discussed in this report. In addition, a brief summary and status of the plans for selecting the utility sites for the experimental wind turbines is also discussed.

**75N32594** NASA-TM-X-71796, 1975; Presented at Frontiers of Technology Conference, 1975, Oklahoma State University.  
**PRELIMINARY RESULTS OF THE LARGE EXPERIMENTAL WIND TURBINE PHASE OF THE NATIONAL WIND ENERGY PROGRAM**

Thomas, R. L. , Sholes, T. , and Sholes, J. E.

The preliminary results of two projects in the development phase of reliable wind turbines designed to supply cost-competitive electrical energy were discussed. An experimental 100 kW wind turbine design and its status are first reviewed. The results of two parallel design studies for determining the configurations and power levels for wind turbines with minimum energy costs are also discussed. These studies predict wind energy costs of 1.5 to 7 cents per kW-h for wind turbines produced in quantities of 100 to 1000 per year and located at sites having average winds of 12 to 18 mph.

**75N21795** NASA-TM-X-71701, 1975; Presented at IEEE/ASME Joint Power Conference, 1975.

**PLANS AND STATUS OF THE NASA-LEWIS RESEARCH CENTER WIND ENERGY PROJECT**

Thomas, R. , Puthoff, R. , Savino, J. , and Johnson, W.

Wind energy is investigated as a source of energy. The wind energy program that is managed by the NASA-Lewis Research Center is described. The Lewis Research Center's Wind Power Office, its organization, plans, and status are discussed. Major elements of the wind power project included are: an experimental 100 kW wind-turbine generator; first generation industry-built and user-operated wind turbine generators; and supporting research and technology tasks.

Proceedings, Second Workshop on Wind Energy Conversion Systems, 1975, NSF-RA-N-75-050, Mitre Corporation (Washington, DC), pp. 477-483.

**VIABILITY OF LARGE WIND TURBINE SYSTEMS -- WORKING GROUP REPORT**

Thomas, R. L.

**74N19705** NASA-TM-X-71523, 1973; Presented at RANN Symposium, 1973, National Science Foundation.

**STATUS OF WIND-ENERGY CONVERSION**

Thomas, R. L. , and Savino, J. M.

The utilization of wind energy is technically feasible as evidenced by the many past demonstrations of wind generators. The cost of energy from the wind has been high compared to fossil fuel systems; a sustained development effort is needed to obtain economical systems. The variability of the wind makes it an unreliable source on a short term basis. However, the effects of this variability can be reduced by storage systems or connecting wind generators to: (1) fossil fuel systems; (2) hydroelectric systems; or (3) dispersing them throughout a large grid network. Wind energy appears to have the potential to meet a significant amount of our energy needs.

**74N16799** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA-TM-X-69786, NSF/RA/W-73-006, pp. 244-253.

**NASA PRESENTATION: PLAN FOR DEVELOPMENT OF WIND ENERGY CONVERSION SYSTEMS**

Thomas, R. L.

A development plan is outlined for wind energy systems that supply reliable energy at a cost competitive with other energy systems. A government-directed industry program with strong university support is recommended that includes meteorological studies to estimate wind energy potentials and determines favorable regions and sites for wind power installations. Key phases of the overall program are wind energy conversion systems, meteorological wind studies, energy storage systems, and environmental impact studies. Performance testing with a prototype wind energy conversion and storage system is projected for Fiscal 1977.

NASA-TM-X-68230 and -68290, 1973.

**THE UTILIZATION OF SOLAR ENERGY TO HELP MEET THE NATION'S ENERGY NEEDS**

Thomas, R. L.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 397-400.

**ENHANCEMENT OF FAR-FIELD SOUND LEVELS BY REFRACTIVE FOCUSING**

Thomson, D. W. , and Roth, S. D.

For meteorological conditions representative of those observed at the Mod-1 HAWT site near Boone, North Carolina, 10 to 20 dB enhancements can occur over ranges of several hundred meters as a result of refractive focusing. Localized enhancements in excess of 20 dB can occur but will probably be of limited duration as a consequence of normal temporally-varying meteorological conditions.

NASA-CR-165403 DOE/NASA/O203-1, 1981.

**DEVELOPMENT REPORT: AUTOMATIC SYSTEM TEST AND CALIBRATION (ASTAC) EQUIPMENT**

Thoren, R. J.

Chapter 11 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

**STRUCTURAL DYNAMIC BEHAVIOR OF WIND TURBINES**

Thresher, R. W. , Mirandy, L. P. , Carne, T. G. , and Lobitz, D. W.

Some of the physical principles and basic analytical tools needed for the structural-dynamic analysis of a horizontal-axis or vertical-axis wind turbine are introduced. This is done through discussions of two subjects that are fundamental building blocks of the understanding of the structural-dynamic behavior of wind turbines: (1) Single-degree-of-freedom dynamic load model of a HAWT blade, and (2) the theoretical and experimental analysis of the vibration modes of a VAWT system.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 161-172.

**RESPONSE OF THE MOD-0A WIND TURBINE ROTOR TO TURBULENT ATMOSPHERIC WIND**

Thresher, R. W. , Holley, W. E. , Hershberg, E. L. , and Lin, S-R.

The major focus of this paper is the description of fluctuating rotor loads caused by atmospheric turbulence, and these are compared with test data from the 125-ft diameter, 200 kW Mod-0A wind turbine as an example. Computations are made for the case of fixed pitch operation and incorporate the influence of a linear mean wind shear. Results presented include power spectral density plots of the wind and turbine outputs for three different mean wind conditions. A discussion of the relative importance of the various turbulence inputs on rotor blade loads is given.

83N19231 NASA-CP-2230 CONF-810752 SERI/CP-635-1273; 838 pp.; Citations to Smith-Putnam Team, pp. 23-33; Wrap-Up Report, pp. 837-8.

**PROCEEDINGS OF THE LARGE HORIZONTAL-AXIS WIND TURBINE CONFERENCE**

Thresher, R. W. , Editor

At this three-day workshop held in Cleveland in July, 1981, more than 300 persons met to hear technical papers contributed by manufacturers, government laboratories, electric utilities, and private research organizations. The technical program emphasized recent experience in building and testing large propeller-type wind turbines, expanding upon the proceedings of three previous DOE/NASA workshops at which design and analysis topics were considered. A total of 41 papers were presented on the following subjects: (1) Current and advanced large wind turbine systems, (2) rotor blade design and manufacture, (3) electric utility activities, (4) research and supporting technology, (5) meteorological characteristics for design and operation, and (6) wind resource assessments and siting.

A highlight of this workshop was the commemoration of the 40th anniversary of the historic Smith-Putnam wind turbine project which produced the first megawatt-size wind power plant in the U.S. Keynote addresses by Messrs. Smith and Putnam are included in these proceedings, together with a contemporary description of the Smith-Putnam wind turbine and project photographs. Descriptions of citations presented to members of the project team who were in attendance are included, with brief biographies.

82N23684 NASA-CP-2185 CONF-810226 SERI/CP-635-1238; 445 pp; Summaries of State-of-the-Art Discussions, pp. 437-445.

**PROCEEDINGS OF THE WIND TURBINE DYNAMICS CONFERENCE**

Thresher, R. W. , Editor

This conference was held in Cleveland in February, 1981. Recent progress in the analysis and prediction of the dynamic behavior of large and small, horizontal- and vertical-axis wind turbine generators is discussed in 53 technical presentations in five disciplines: Aerodynamics, structural dynamics, rotor dynamics, control dynamics, and acoustics. The following issues were addressed: (1) the adequacy of state of the art analysis tools for designing the next generation of wind power systems; (2) the use of state of the art analysis tools designers; and (3) verifications of theory which might be lacking or inadequate. Contributors include universities, manufacturers, government laboratories, and private research organizations. Summaries of informative discussions on each discipline as well as the questions and answers which followed each paper are documented in the proceedings.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 87-99.

#### **WIND RESPONSE CHARACTERISTICS OF HORIZONTAL AXIS WIND TURBINES**

Thresher, R. W. , Holley, W. E. , and Jafarey, N.

A statistical description of the wind input to a HAWT rotor, including all three wind components, is used in this analysis, together with linear wind gradients across the rotor disk, quasi-static aerodynamic theory, and an elementary structural-dynamic model involving only a few degrees of freedom. Analytical results are presented for the following two wind systems of vastly different size: (1) An 8-kW HAWT with a three-bladed, downwind, free-yaw rotor 16.67 ft in diameter, and (2) a 2.5-MW HAWT with a three-bladed, upwind, fixed-yaw rotor 150 ft in diameter. It was found that the longitudinal turbulence input and the two horizontal and vertical gradients across the disk are of equal importance when computing dynamic responses, and these three inputs together comprise the major excitation source for HAWTs. (See companion paper by Holley, Thresher, and Lin at same conference.)

NASA-CR-174677 DOE/NASA/0337-1, 1983.

#### **CORROSION FATIGUE OF HIGH STRENGTH FASTENER MATERIALS IN SEA WATER**

Tipton, D. J.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 135-136.

#### **STATUS AND APPLICABILITY OF SOLID POLYMER ELECTROLYTE TECHNOLOGY TO ELECTROLYTIC HYDROGEN AND OXYGEN PRODUCTION**

Titterton, W. A.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 23-26.

#### **INTRODUCTION TO VOIGT'S WIND POWER PLANT**

Tompkin, J.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 121-122.

#### **VOIGHT VARIABLE SPEED DRIVE**

Tompkin, J.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 357-373.

#### **THE USEFUL POTENTIAL OF USING EXISTING DATA TO UNIQUELY IDENTIFY PREDICTABLE WIND EVENTS AND REGIMES -- PART I**

Trettel, D. W. , Aquino, J. T. , Piazza, T. R. , Taylor, L. E. , and Trask, D. C.

Correlations are described between standard meteorological data and wind power generation potential which can be useful to electric-utility load dispatchers . Hourly wind data are analyzed for four sites, each exhibiting unique physiography. Synoptic weather maps and tables are presented to illustrate various wind regimes at these sites. (See paper by C. Notis in same conference for Part II.)

76N14605 NASA-TM-X-71831, 1975.

#### **INSTALLATION AND INITIAL OPERATION OF A 4100 WATT WIND TURBINE**

Tryon, H. B. , and Richards, T.

The results are presented of 211 days of operation of the 4.1 kilowatt wind turbine, which was the largest commercially

available wind turbine. The wind turbine, electric controls and load bank, and the pivoted tower are described.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 711-726.

#### **AN OVERVIEW OF LARGE WIND TURBINE TESTS BY ELECTRIC UTILITIES**

Vachon, W. A. , and Schiff, D.

A summary is provided of recent plans and experiences on current large wind turbine tests being conducted by electric utilities in the U.S. , outside of the federal research and development program. Key tests and test instrumentation are described, and recent results are given. During the past year many of the utility test programs have encountered difficulties that led to specific design changes, although test results to date continue to indicate that long-term machine performance and cost-effectiveness are achievable.

Proceedings, Windpower '85 Conference, 1985, American Wind Energy Association (Washington, DC), pp. 124-129.

#### **WESTINGHOUSE 600-kW WIND TURBINE DESIGN**

VanBibber, L. E. , and Kelly, J. L.

A description is given of a commercially-available large-scale HAWT designed for a marine environment and based on a scale-up of the NASA Mod-0A turbine with features such as upwind rotor, teetering, and a shell tower adapted from the Mod-2 design. Blades are laminated wood/epoxy with a modified LS(1)-04XX profile and are fully pitchable. Specifications, power curve, annual energy capture, nacelle arrangement, tower and foundation, pitch control mechanism, and yaw drive system are shown.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 96-102.

#### **VERTICAL AXIS WIND ROTORS - STATUS AND POTENTIAL**

Vance, W.

74N16757 Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 174-176.

#### **WIND UTILIZATION IN REMOTE REGIONS - AN ECONOMIC STUDY**

VanSant, J. H.

90N70771 and 85N73389 NASA-TM-87484 Revised, and 75N13380 NASA-TM-X-71634, 1975; Presented at 4th Annual Regulatory Information Systems Conference (St. Louis), 1974.

#### **WIND ENERGY DEVELOPMENTS IN THE 20TH CENTURY**

Vargo, D. J.

Wind turbine systems of the past are reviewed and wind energy is re-examined as a future source of power. Various phases and objectives of the Wind Energy Program are discussed. Conclusions indicate that wind generated energy must be considered economically competitive with other power production methods.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111. pp. 325-342.

#### **THE MOD-1 STEEL BLADE**

VanBronkhorst, J.

Since September of 1977, design, development, fabrication, testing and transport of two 100 foot metal blades for the Mod-1 WTS has been completed, activities that are summarized in this paper. Because the metal blade design was started late in the project, many of the design requirements were restrictive for the metal blade concept, particularly the maximum weight requirement. Unique design solutions and fabrication procedures with minimum tooling are described.

75N26497 NASA-TM-X-71745; Presented at Southeastern Conference on Applications of Solar Energy, 1975, Alabama University.

#### **SUMMARY OF NASA LEWIS RESEARCH CENTER SOLAR HEATING AND COOLING AND WIND ENERGY PROGRAMS**

Vernon, R. W.

Plans for the construction and operation of a solar heating and cooling system in conjunction with a office building being

constructed at Langley Research Center, are discussed. Supporting research and technology includes: testing of solar collectors with a solar simulator, outdoor testing of collectors, property measurements of selective and nonselective coatings for solar collectors, and a solar model-systems test loop. The areas of a wind energy program that are being conducted include: design and operation of a 100-kW experimental wind generator, industry-designed and user-operated wind generators in the range of 50 to 3000 kW, and supporting research and technology for large wind energy systems. An overview of these activities is provided.

**83N19233** Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 69-85.

#### **FIXED PITCH ROTOR PERFORMANCE OF LARGE HORIZONTAL AXIS WIND TURBINES**

Viterna, L. A. , and Corrigan, R. D.

Experimental fixed pitch wind turbine performance data is presented for both the DOE/NASA Mod-0 and the Danish Gedser wind turbines. Furthermore, a method for calculating the output power from large fixed pitch wind turbines is presented. Modifications to classical blade element momentum theory are given that improve correlation with measured data. Improvement is particularly evident in high winds (low tip speed ratios) where aerodynamic stall occurs as the blade experiences high angles of attack.

**82N33830** NASA-TM-82944 DOE/NASA/20320-41, 1982; also Proceedings, Fifth Biennial Wind Energy Conference and Workshop, Vol. II, 1981, SERI-CP-635-1340, National Renewable Energy Laboratory (Golden, Colorado), pp. 265-280.

#### **THEORETICAL AND EXPERIMENTAL POWER FROM LARGE HORIZONTAL-AXIS WIND TURBINES**

Viterna, L. A. , and Janetzke, D. C.

A method for calculating the output power from large horizontal-axis wind turbines is presented. Modifications to the airfoil characteristics and the momentum portion of classical blade element-momentum theory are given that improve correlation with measured data. Improvement is particularly evident at low tip-speed ratios where aerodynamic stall can occur as the blade experiences high angles of attack. Output power calculated using the modified theory is compared with measured data for several large wind turbines. These wind turbines range in size from the DOE/NASA 100 kW Mod-0 (38 m rotor diameter) to the 2000 kW Mod-1 (61 m rotor diameter). The calculated results are in good agreement with measured data from these machines.

**82N21714** NASA-TM-82794 DOE/NASA/20320-36; Presented at International Conference on Noise Control Engineering, 1982.

#### **METHOD FOR PREDICTING IMPULSIVE NOISE GENERATED BY WIND TURBINE ROTORS**

Viterna, L. A.

Large wind turbines can generate both broad band and impulsive noises. These noises can be controlled by proper choice of rotor design parameters such as rotor location with respect to the supporting tower, tower geometry and tip speed. A method was developed to calculate the impulsive noise generated when the wind turbine blade experiences air forces that are periodic functions of the rotational frequency. This phenomenon can occur when the blades operate in the wake of the support tower and the nonuniform velocity field near the ground due to wind shear. Results from this method were compared with measured sound spectra taken at locations of one to two rotor diameters from the DOE/NASA Mod-1 wind turbine. The calculated spectra generally agreed with the measured data in both the amplitude of the predominant harmonics and the roll of rate with frequency. Measured sound pressure levels far from the Mod-1 (15 rotor diameters), however, were higher than predicted. Simultaneous measurements in the near and far field indicated that the propagation effects could enhance the sound levels by more than 10 dB above that expected by spherical dispersion. These propagation effects are believed to be due to terrain and atmospheric characteristics of the Mod-1 site.

**82N23730 and 81N21537** NASA-TM-81737 DOE/NASA/20366-1, 1981; also Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 411-418.

#### **THE NASA-LERC WIND TURBINE SOUND PREDICTION CODE**

Viterna, L. A.

Since regular operation of the DOE/NASA Mod-1 wind turbine began in October 1979 about 10 nearby households have complained of noise from the machine. Development of the NASA-LeRC with turbine sound prediction code began in May 1980 as part of an effort to understand and reduce the noise generated by Mod-1. Tone sound levels predicted with this code are in generally good agreement with measured data taken in the vicinity Mod-1 wind turbine (less than 2 rotor diameters). Comparison in the far field indicates that propagation effects due to terrain and atmospheric conditions may be amplifying

the actual sound levels by about 6 dB. Parametric analysis using the code has shown that the predominant contributions to Mod-1 rotor noise are (1) the velocity deficit in the wake of the support tower; (2) the high rotor speed; and (3) off-optimum operation.

**81N76357** NASA-TM-80462; also Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 35-42; reprinted from Turbine Topics, Volume 1, Number 3, Jun. 1943, 6 p.

#### **THE SMITH-PUTMAN WIND TURBINE**

Voaden, G. H.

A contemporary account is given by the Assistant Chief Engineer of the historic Smith-Putnam wind turbine constructed at Grandpa's Knob near Rutland, Vermont, in 1941. The two-bladed rotor was 175 feet in diameter and the rated power of the generator was 1,000 to 1,250 kW. Thirteen photographs show project progress and staff. The Smith-Putnam turbine is generally recognized as the first megawatt-scale wind power plant delivering utility-grade AC power directly into an electric network in the U.S. It also pioneered the wind turbine configuration most-likely to be cost-effective: A propeller-type rotor driving a generator through a step-up gearbox, all mounted on a supporting tower and turning to face the wind.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 121-128.

#### **AN OVERVIEW OF FATIGUE FAILURES AT THE ROCKY FLATS WIND SYSTEM TEST CENTER**

Waldon, C. A.

This paper identifies potential design problems in small-scale wind turbines in order to improve product quality and reliability. Mass-produced components such as gearboxes, generators, bearings, etc., are generally reliable because of widespread uniform use in other industries. Likelihood of failure increases in the interfacing of these components and in components designed for a specific small-scale wind turbine. Problems relating to structural integrity are discussed and analyzed according to techniques currently used in quality assurance programs in other industries.

Proceedings, Wind Energy Expo '82 and National Conference, 1982, American Wind Energy Association (Washington, DC), 31-32.

#### **STATUS OF THE WTS-3 AND WTS-4**

Walker, C. C.

Brief description of Hamilton Standard wind turbine program is given, with two site photographs of the WTS-4 4-MW HAWT near Medicine Bow, Wyoming, a shop photograph of the nacelle under construction in Sweden, and a shop photograph of a 38-m composite blade during filament winding in East Granby, Connecticut.

Proceedings, Large Wind Turbine Design Characteristics and R&D Requirements Conference, 1979, NASA CP 2106, DOE CONF-7904111, pp. 363-374.

#### **RESULTS OF A UTILITY SURVEY OF THE STATUS OF LARGE WIND TURBINE DEVELOPMENT**

Watts, A. , Quraeshi, S. , and Rowley, L. P.

The overall objective of this survey, commissioned by Hydro-Quebec, is to examine wind energy conversion systems from a utility viewpoint to establish the state-of-the-art with regard to (1) availability of the type of machines, (2) quality of power generation, (3) suitability of WECS for electrical grid systems, (4) reliability of the WECS, and (5) economics. The methodology employed consists of survey of literature; visits to installations of interest in Europe and North America; discussions with designers, operators, and planners; and a design study involving state-of-the-art WECS.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 741-755.

#### **WTS-4 SYSTEM VERIFICATION UNIT FOR WIND/HYDROELECTRIC INTEGRATION STUDY**

Watts, A. W.

This paper discusses a Bureau of Reclamation study to investigate the concept of integrating 100 MW of wind power from megawatt-scale wind turbines with the Federal hydroelectric system. One large wind turbine -- a 4 MW WTS-4 HAWT -- was purchased through the competitive bid process and is now being installed to serve as a system verification unit. Hamilton Standard was awarded a contract to furnish and install the wind turbine at a site near Medicine Bow, Wyoming, and the NASA Lewis Research Center agreed to provide project technical management. The purposes of this field testing are to fully evaluate the wind/hydro integration concept, make technical evaluations of the hardware design, train personnel, evaluate operation and maintenance, and evaluate associated environmental impacts. The WTS-4 unit is scheduled to be operational in June 1982. Data from it and a second unit -- a 2.5-MW Mod-2 HAWT -- will be used to prepare a final design for a 100-MW wind power station if the Congress authorizes the project.

NASA-TT-F-17379, 1977, Technical Translation.

**THE OPTIMUM CONFIGURATION OF ROTOR BLADES FOR HORIZONTAL WIND ENERGY CONVERTERS**  
Weber, W.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 727-739.

**UTILITY EXPERIENCE WITH TWO DEMONSTRATION WIND TURBINE GENERATORS**  
Wehrey, M. C.

Southern California Edison's experience with two wind turbines -- the 3 MW Bendix/Schachle HAWT and a 500 kW Alcoa VAWT -- is summarized, and the problems encountered with the operation of both machines are discussed. This is a one to two year test program during which turbine performance, system operations, and environmental impacts will be assessed in order to establish design criteria for future wind power plants. The information needs of a utility planning to use wind power generation are also discussed briefly.

Chapter 13 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

**A UTILITY PERSPECTIVE ON WIND ENERGY**  
Weinberg, C. J. , and Ancona, D. F. , III

As operating experience with wind power plants accumulates, many of the early fears of adverse impacts on critical performance and economic factors in utility systems are being dispelled. Topics discussed include introduction of new technology into utilities, utility cost-estimation models, value of wind-generated energy to a utility, selecting an energy portfolio, and technical issues in transmission and power quality.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 239-258.

**LOW-COST COMPOSITE BLADES FOR THE MOD-0A WIND TURBINES**  
Weingart, O.

Objectives of this project, carried out by Structural Composites Industries, were to identify low-cost techniques for the design and fabrication of blades for an intermediate-scale wind turbine, and to assess the applicability of these techniques to both larger and smaller turbines. The selected blade design consists of three cells all fabricated by the Transverse Filament Tape (TFT) method of composite material fabrication. Topics include a blade description; root-end fitting; hub adapter; balancing, ice detection, and lightning protection; materials of construction; structural analysis and blade structural properties; manufacturing consideration; quality assurance, tooling design, fabrication, handling, and shipping; applicability to other sizes; inspection results; and cost and weight analysis.

NASA-CR-165342 DOE/NASA/0100-1, 1981.

**DESIGN, EVALUATION, AND FABRICATION OF LOW-COST COMPOSITE BLADES FOR INTERMEDIATE-SIZE WIND TURBINES**  
Weingart, O.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 389-395.

**GE MOD-1 NOISE STUDY**  
Wells, R. J.

Noise studies of the Mod-1 wind turbine generator are summarized, and a simple mathematical model is presented which is adequate to correlate the sound levels found near the machine. A simple acoustic measure is suggested for use in evaluating far-field sound levels. Use of this measure as input to a currently-available sound complaint prediction program is discussed. Results are described of a recent statistical survey relative to the far-field variation of this acoustic measure caused by atmospheric effects.

NASA-CR-168109 DOE/NASA/3303-3, 1982.

**SIMPLIFIED AEROELASTIC MODELING OF HORIZONTAL AXIS WIND TURBINES**  
Wendell, J. H.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 46-52.

**SURFACE WIND CHARACTERISTICS OF SOME ALEUTIAN ISLANDS**

Wentink, T. Jr.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 47-52.

**COMPARATIVE WIND TUNNEL TESTS OF NACA 23024 AIRFOILS WITH SEVERAL AILERON CONFIGURATIONS**

Wentz, W. H. , and Snyder, M. H.

Research efforts at Wichita State University are reviewed on the design and evaluation of aerodynamic braking devices, including a variety of aileron configurations and spoilers located at both the leading and trailing edges of blades. Topics discussed are analytical modeling, wind tunnel tests, and (for some configurations) full-scale rotor tests. Results show that trailing edge devices require fairly large chords to achieve the required control authority. Analysis and wind tunnel test data indicate that several options are available to the designer to provide aerodynamic braking without full-chord pitch control.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 41-49.

**ANALYTICAL STUDIES OF NEW AIRFOILS FOR WIND TURBINES**

Wentz, W. H. Jr. , and Calhoun, J. T.

Results are presented of computer studies analyzing gains associated with utilizing new airfoils for large wind turbine rotors. Attempts to include 3-dimensional stalling effects are inconclusive. It is recommended that blade pressure measurements be made to clarify the nature of blade stalling, and that new NASA laminar-flow airfoils be used as wind turbine rotor blade profiles.

NASA-CR-159856 DOE/NASA/3277-1, 1980.

**FEASIBILITY STUDY OF AILERON AND SPOILER CONTROL SYSTEMS FOR LARGE HORIZONTAL AXIS WIND TURBINES**

Wentz, W. H. Jr. , Calhoun, J. T. , and Snyder, M. H.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 89-95.

**THE EFFECT OF AERODYNAMIC PARAMETERS ON POWER OUTPUT OF WINDMILLS**

Wiesner, W.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 8-10.

**MOTION PICTURE HISTORY OF THE ERECTION AND OPERATION OF THE SMITH-PUTNAM WIND GENERATOR**

Wilcox, C.

**85A10652** Presented at American Power Conference, 1984, 10 pp.

**MEASURED EFFECTS OF WIND TURBINE GENERATION AT THE BLOCK ISLAND POWER COMPANY**

Wilreker, V. F. , Smith, R. F. , Stiller, P. H. , Scott, G. W. , and Shaltens, R. K.

Data measurements made on the NASA MOD-0A 200-kW wind-turbine generator (WTG) installed on a utility grid form the basis for an overall performance analysis. Fuel displacement/savings, dynamic interactions, and WTG excitation (reactive-power) control effects are studied. Continuous recording of a large number of electrical and mechanical variables on FM magnetic tape permit evaluation and correlation of phenomena over a bandwidth of at least 20 Hz. Because the wind-power penetration reached peaks of 60 percent, the impact of wind fluctuation and wind-turbine/diesel-utility interaction is evaluated in a worst-case scenario. The speed-governor dynamics of the diesel units exhibited an under-damped response, and the utility operation procedures were not altered to optimize overall WTG/utility performance. Primary findings over the data collection period are: a calculated 6.7-percent reduction in fuel consumption while generating 11 percent of the total electrical energy; acceptable system voltage and frequency fluctuations with WTG connected; and applicability of WTG excitation schemes using voltage, power, or VARS as the controlled variable.

NASA-CR-168318 DOE/NASA/0354-1, 1984.

**WIND TURBINE GENERATOR INTERACTION WITH CONVENTIONAL DIESEL GENERATORS ON BLOCK ISLAND, RHODE ISLAND -- VOLUME I: EXECUTIVE SUMMARY**

Wilreker, V. F. , Smith, R. F. , Stiller, P. H. , Scott, G. W. , and Kruse, V. J.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 41-46.

**PRELIMINARY ANALYSIS OF DYNAMIC STALL EFFECTS ON A 91-METER WIND TURBINE ROTOR**  
Wilson, R. E.

The results of an analytic investigation of HAWT rotor aerodynamics are presented, including dynamic stall effects on loads and power output of the Mod-2 2.5-MW wind turbine. Dynamic stall was modeled using the Boeing-Gormont approach, with the blades treated as rigid bodies teetering about a fixed axis. Blade flatwise bending moments near the hub were determined with and without dynamic stall for a variety of spatial variations in local wind speed due to wind shear and yaw error. Predicted mean flatwise bending moments were found to be in good agreement with test results, with little dynamic stall effects. Calculated cyclic bending moments, however, were significantly higher when a dynamic stall model was used but did not reach the level of measured cyclic loads. A simple closed-form expression for the inviscid wake of a HAWT is also presented in this paper, together with an explanation for the observed tendency of downwind free-yaw rotors to operate upwind under certain conditions.

Chapter 5 in Wind Turbine Technology, D. A. Spera, Editor, 1994, ASME Press (New York).

**AERODYNAMIC BEHAVIOR OF WIND TURBINES**

Wilson, R. E.

Basic principles and aerodynamic theories are discussed, starting from the actuator disk model of a HAWT rotor, extending through the Glauert optimum actuator disk model, to the strip theory which is the current mainstay of HAWT aerodynamic design and analysis. Various corrections, including thrust coefficient modifications, tip-loss models, and gap corrections, are developed. Comparisons are made between test data, strip theory, and free-vortex calculations.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 3-7.

**AERODYNAMIC POTPOURRI**

Wilson, R. E.

Aerodynamic developments for VAWTs and HAWTs are given that relate to performance and aerodynamic loading. Included are (1) a fixed-wake aerodynamic model of the Darrieus VAWT; (2) experimental results that suggest the existence of a laminar flow Darrieus turbine; (3) a simple aerodynamic model for the turbulent windmill/vortex ring state of HAWT rotors; and (4) a yawing moment model of a rigid-hub HAWT, that is related to blade coning.

**74N16757** Proceedings, Wind Energy Conversion Systems Conference, 1973, NASA- TM-X-69786, NSF/RA/W-73-006, pp. 180-185.

**THE OREGON STATE UNIVERSITY WIND STUDIES**

Wilson, R. E.

**79N28727** NASA-TM-79200 DOE/NASA/1028-79/24, 1979.

**DESIGN, FABRICATION, AND INITIAL TEST OF A FIXTURE FOR REDUCING THE NATURAL FREQUENCY OF THE MOD-0 WIND TURBINE TOWER**

Winemiller, J. R. , Sullivan, T. L. , Sizemore, R. L. , and Yee, S. T.

It was desired to observe the behavior of a two bladed wind turbine where the tower first bending natural frequency is less than twice the rotor speed. The system then passes through resonance when accelerating to operating speed. The frequency of the original Mod-0 tower was reduced by placing it on a spring fixture. The fixture is adjustable to provide a range of tower bending frequencies. Fixture design details are given and behavior during initial operation is described.

NASA-TT-F-15,348, 1974, Technical Translation.

**THE ECONOMY AND PRACTICALITY OF LARGE SCALE WIND GENERATION STATIONS (CONCLUSION)**  
Witte, H.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 245-253.

**SWECS TOWER DYNAMICS ANALYSIS METHODS AND RESULTS**

Wright, A. D. , Sexton, J. H. , Butterfield, C. P. , and Thresher, R. W.

At the Rocky Flats Wind Systems Center, several different dynamics analysis methods and computer codes are used to determine the natural frequencies and mode shapes of both guyed and free-standing wind turbine towers. These are described, and analysis results for the two types of towers are presented. Advantage and disadvantages in the use and accuracy of each method are discussed.

**78N19626** Proceedings, Wind Turbine Structural Dynamics Conference, 1977, NASA CP 2034, DOE CONF-771148, pp. 103-108.

#### **INFLUENCE OF WIND TURBINE FOUNDATION STIFFNESS ON NATURAL FREQUENCY**

Yee, S. T.

The 200 kW Mod-0A wind turbine was modeled using a 3 lumped mass-spring system for the superstructure and a rotational spring for the foundation and supporting soil. Natural frequencies were calculated using soil elastic moduli varying from 3,000 to 22,400 psi. The reduction in natural frequencies from the rigid foundation case ranged up to 20 percent.

**77N26613** NASA-TM-X-73670 ERDA/NASA-1004/77/1, 1977.

#### **VIBRATION CHARACTERISTICS OF A LARGE WIND TURBINE TOWER ON NON-RIGID FOUNDATIONS**

Yee, S. T. , Chang, T. Y. P. s, Scavuzzo, R. J. , Timmerman, D. H. , and Fenton, J. W.

Vibration characteristics of the Mod-0A wind turbine supported by nonrigid foundations were investigated for a range of soil rigidities. The study shows that the influence of foundation rotation on the fundamental frequency of the wind turbine is quite significant for cohesive soils or loose sand. The reduction in natural frequency can be greater than 20 percent. However, for a foundation resting on well graded, dense granular materials or bedrock, such effect is small and the foundation can be treated as a fixed base.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 35-40.

#### **THE VELOCITY FIELD OF A SYSTEM OF UNSTEADY CYCLOIDAL VORTICIES**

Young, B. J.

An essential difference between two-dimensional and three-dimensional models of cycloidal rotors is the presence of unsteady trailing cycloidal vortices in the wake. The velocity induced by these vortices is the primary mechanism producing flow retardation for low span/radius ratio, finite blade number rotors. An idealized rigid wake model of finite blade cycloidal rotors is used to investigate some cycloidal rotor problems.

Proceedings, Sixth Biennial Wind Energy Conference and Workshop, 1983, American Solar Energy Society (Boulder, Colorado), pp. 121-132.

#### **INSTALLATION, CHECKOUT, AND ACCEPTANCE TESTING OF THE HAMILTON STANDARD 4-MEGAWATT WIND TURBINE SYSTEM (WTS-4)**

Young, P. , and Hasbrouck, T. M.

This paper describes the transportation and installation of the WTS-4 near Medicine Bow, Wyoming, including two, single-piece, 125-ft long blades and the 152-ton, 69 x 15 x 12 ft nacelle. Procedures employed in erecting the 260-ft high tower and lifting the 215-ton nacelle/rotor combination are discussed and pictured. Results of initial system operation and testing are also described.

Proceedings, Wind Turbine Dynamics Conference, 1981, NASA CP 2185, DOE CONF-810226, pp. 221-223.

#### **EXPERIENCE ON THE USE OF MOSTAB-HFW COMPUTER CODE FOR HORIZONTAL-AXIS WIND TURBINES**

Yu, Y-Y.

Three topics are covered, dealing with the frequencies of a rotating beam, the use of the fundamental mode of a uniform cantilever beam, and the analysis of resonance dwell. Immensely high peak loads were generated by the code for resonance dwell, indicating further need for including structural damping and for transient analysis capability. The effect of structural damping, newly incorporated in the code, is finally described.

Collected Papers on Wind Turbine Technology, D. A. Spera, Editor, NASA CR-195432, 1995, pp. 139-152.

#### **Comparison of Measured and Calculated Dynamic Loads for the Mod-2 2.5-MW Wind Turbine System**

Zimmerman, D. K. , Shipley, S. A. , and Miller, R. D.

This paper presents test setups, loads instrumentation, loads data comparisons, and test/analysis correlations with DYLOSAT computer model predictions. The latter use both the NASA Interim Turbulence Model and rotationally-sampled winds as inputs. Rotational sampling is demonstrated to have the potential to improve the test/analysis correlations.

Assessment of the effects on fatigue loads of vortex generators, site topography, and turbine-to-turbine differences are given. The adequacy of current load prediction techniques is evaluated and recommendations for improvements are made.

Proceedings, Fourth ASME Wind Energy Symposium, 1985, American Society of Mechanical Engineers (New York), pp. 23-32.

#### **MOD-2 WIND TURBINE LOADS TEST CORRELATIONS**

Zimmerman, D. K. , and Shipley, S. A.

The results of a test program conducted on the Mod-2 2.5-MW HAWTs near Goldendale, Washington, are presented. Objectives of this program are to update fatigue load spectra, discern site and machine differences, measure vortex generator effects, and evaluate rotational sampling techniques for calculating spatial wind turbulence effects on loads. Test setup, loads instrumentation, loads data comparisons, and test/analysis correlations are all presented in this paper. An assessment is given of the conditions and parameters investigated, the prediction models used, and the importance to fatigue load prediction of vortex generators, site dependence, and machine differences.

Proceedings, Large Horizontal Axis Wind Turbine Conference, 1981, NASA CP 2230, DOE CONF-810752, pp. 287-302.

#### **THE DEVELOPMENT AND MANUFACTURE OF WOOD COMPOSITE WIND TURBINE ROTORS**

Zuteck, M. D.

This paper considers the physical properties, operational experience, and construction methods of the wood/epoxy composite blades for the 200-kW 38-m diameter Mod-0A wind turbines. Blades of this type have now accumulated over 10,000 hours of successful operation at the Kahuku, Hawaii, and Block Island, Rhode Island, sites. That body of experience is summarized and related to the structural concepts and design drivers which motivated the original design and choice in interior layout. Actual manufacturing experience and associated low first-unit costs for these blades, as well as projections for high-production rates, are presented. Application of these construction techniques to a wide range of other blade sizes is also considered.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE April 1995	3. REPORT TYPE AND DATES COVERED Final Contractor Report		
4. TITLE AND SUBTITLE Bibliography of NASA-Related Publications on Wind Turbine Technology 1973-1995		5. FUNDING NUMBERS WU-776-33-41 C-NAS3-25776		
6. AUTHOR(S) David A. Spera				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DASCON Engineering 29301 Wolf Road Bay Village, Ohio 44140		8. PERFORMING ORGANIZATION REPORT NUMBER E-9597		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CR-195462		
11. SUPPLEMENTARY NOTES Prepared under Interagency Agreement No. DE-AI01-76ET20320. Project Manager, Larry H. Gordon, Aerospace Technology Facilities Division, NASA Lewis Research Center, organization code 5700, (216) 977-7448.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 44  This publication is available from the NASA Center for Aerospace Information, (301) 621-0390.		12b. DISTRIBUTION CODE DOE Category UC-60		
13. ABSTRACT (Maximum 200 words) A major program of research and development projects on wind turbines for generating electricity was conducted at the NASA Lewis Research Center from 1973 to 1988. Most of these projects were sponsored by the U.S. Department of Energy (DOE), as a major element of its Federal Wind Energy Program. One other large-scale wind turbine project was sponsored by the Bureau of Reclamation of the Department of Interior (DOI). The peak years for wind energy work at Lewis were 1979-80, when almost 100 engineers, technicians, and administrative personnel were involved. From 1988 to their conclusion in 1995, NASA wind energy activities have been directed toward the transfer of technology to commercial and academic organizations. Wind energy activities at NASA can be divided into two broad categories which were closely related and often overlapping: (1) Designing, building, and testing a series of 12 large-scale, experimental, horizontal-axis wind turbines (HAWTs); and (2) conducting supporting research and technology (SR&T) projects. The purpose of this bibliography is to assist those active in the field of wind energy in locating the technical information they need on wind power planning, wind loads, turbine design and analysis, fabrication and installation, laboratory and field testing, and operations and maintenance. This bibliography contains approximately 620 citations of publications by over 520 authors and co-authors. Sources are: (1) NASA reports authored by government, grantee, and contractor personnel, (2) papers presented by attendees at NASA-sponsored workshops and conferences, (3) papers presented by NASA personnel at outside workshops and conferences, and (4) outside publications related to research performed at NASA/DOE wind turbine sites.				
14. SUBJECT TERMS Wind turbine; Wind energy; Wind power		15. NUMBER OF PAGES 129		
		16. PRICE CODE A07		
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	